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# **Wastewater Flow Measurement in Sewers Using Ultrasound**

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WASTEWATER FLOW MEASUREMENT IN SEWERS  
USING ULTRASOUND

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## FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and Development is that necessary first step in problem solution and it involves defining the problems, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

As part of these activities, the study described herein demonstrated and evaluated a new technique for measurement of sewage flow utilizing ultrasonic measurements of stream depth and velocity.

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*See report describes*

# ABSTRACT

A new technique for measurement of sewage volume flow utilizing ultrasonic measurements of depth and velocity was demonstrated and evaluated. The new technique, requiring no costly construction for installation, is usable for open channel or partially full measurements. The flow technique can accomplish measurement accuracies from 2 to 5% under conditions of rapidly changing levels, surcharging, and back-up conditions. Two installations were accomplished on existing sewers in the Milwaukee Sewage System, one 12½ feet and the other 5 feet in diameter. A continuous flow record was displayed for each meter and performance of the meter installations was compared with magnetic flow meters at one site and head velocity relations on the other site. Relationship between average volume flow, water level, and average velocity along selected horizontal chords of the sewer cross section were determined. The unit installed on the 5 foot diameter sewers operated for a period in excess of 18 months without failure and has required only routine maintenance. The flow technique provides accurate measurement over a range of depths from 25% to full depth in the sewer and from zero to the full flowing velocity of the fluid in the sewer. No deterioration of ultrasonic transducer probes has been detected indicating their suitability for use in the sewer environment.

This report was submitted in fulfillment of Project No. 11024 FVQ by the Milwaukee Sewerage Commission under the sponsorship of the U. S. Environmental Protection Agency. This report covers the period April 1, 1971 to June 30, 1974, and work was completed as of September 30, 1975.

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## SECTION I

### CONCLUSIONS

1. Ultrasonic velocity measurement equipment in conjunction with ultrasonic level measurement equipment can be utilized for the measurement of sewage volume flow.
2. At a typical cost of \$10,000 to \$12,000 for a height-velocity system (including probes, indicator, totalizer and recorder), the equipment is sufficiently low in cost to achieve general use, can be conveniently installed in new or existing sewers, requires a minimum maintenance, and is suited for long term operation in the sewer environment.
3. Installation of the equipment does not normally require special constructions and/or metering pits or vaults.
4. Between 25% of channel depth and surcharged conditions the correlation between the average chordal velocity and the average area velocity is sufficiently predictable to enable the average chordal velocity level and area functions to be easily integrated electronically providing flow information accurate to within approximately 2%.
5. Pulse leading edge detection in the ultrasonic velocity electronics is more susceptible to fluctuations in solids loading and/or entrained air densities resulting in fluctuations in velocity measurement than is peak pulse detection.
6. The velocity measurement portion has a 20 to 1 turn down capability and with the velocity probes mounted at the 25% level the level measurement portion is limited to a 4 to 1 turn down. This gives the system an 80 to 1 turn down capability which well exceeded the flow ranges experienced. System operation is limited to the turbulent flow regime and flow media which do not contain large quantities of entrained air.

## SECTION II

### RECOMMENDATIONS

Operation of the flowmeters at their present locations should be continued for as long as possible to determine what, if any, deterioration of the probes might occur.

The effect of entrained air on transmission using probes having crystals cut for higher frequencies should be investigated.

The method of using ultrasonic velocity and level measuring equipment should also be developed to operate in relatively smaller line sizes of 6 to 36 inch diameters. Unlike the ultrasonic sewage metering system, present flume and weir devices have limited rangeability and are inoperative under surcharge conditions.

Many sources within municipalities, consulting engineering firms and state and federal pollution control agencies have identified the need for reliable semi-portable sewage metering equipment particularly for infiltration and loading studies in combined sewer networks. Consequently, the development of a portable ultrasonic sewage flow monitoring unit is desirable.

Until such time as the interference caused by entrained air is virtually, if not completely, eliminated, future installations of the ultrasonic sewage flow meter should be limited to those sites which do not immediately follow either pumping or outfalls which contribute a significant portion of the total volume at that site. In addition, those sites where agitation, outfall or pumping have caused the surface to be foam covered are unsuitable for the level monitoring equipment in that

the foam surface absorbs the ultrasonic energy, precluding an echo. The use of a load-length product to estimate the effects of entrained solids loads in the transmission path length is advised, although most applications appear to be well below recommended limits of 5,000 m-mg/l.



### SECTION III

#### INTRODUCTION

##### PURPOSE AND SCOPE

Wastewater flow measurement with adequate accuracy, rangeability and reliability is the keystone of wastewater regulation, namely the exercise of control over sewage quantity, rate of travel and routing in the sewerage system. Among other benefits, effective regulation of a combined sewerage system minimizes outflow of raw sewage during storm conditions. However, effective regulation requires effective flow measurement, and the state-of-the art of instrumentation for sewage flow has been decidedly in arrears of metering technology developed for other applications. Thus the primary purpose of this demonstration was to advance a practical, low cost, wide range sewage flow measurement technique for general use in existing storm, sanitary and combined sewers.

In a sanitary sewer system with minimal ground water infiltration, flow is reasonably steady and present metering practice requires measurement of volume flow using a pressure head producing device such as a flume or a weir. Open channel metering structures of this type are subject to debris and sedimentation accumulation and importantly, require loss of pressure head for operation. Present practice for the measurement of pressure head in these devices corresponds to the use of either bubbler gauges or float level gauges, either of which are subject to fouling due to stringy, greasy and sticky entrainments. In any of the metering structures presently employed for volume flow measurement the devices are unidirectional and subject to very large errors under conditions of submergence or nongravitational discharge conditions. In a storm sewer, or a combined sanitary and storm sewer system, flow is subject to transients in level and velocity due to rainfall runoff with occasional

backflows and surcharging. Further, in a sewage system regulated for minimization of raw sewage discharge into a watershed, control practices involve sewer gating, pumping and temporary retention in lesser used interceptors and trunks. These practices generally alter the characteristics of sewage flow bringing about unsteady flow, high sewage levels accompanied by zero flow in the conduits used for temporary storage, high and rapidly changing sewage levels, and occasional surcharging and backflow conditions. Flow properties of this sort render the performance of conventional open channel metering structures unsatisfactory and contribute to the need for a sewer meter designed specifically for the application.

With these points in mind, two metering sites were selected which were felt to be typical in that both had downstream conditions which at times invalidated the assumption of gravity flow. Furthermore, both sites were partially filled, circular conduits one of which could conceivably be subject to surcharging.

#### CONCEPTS

The sewer flow measurement technique utilized in this demonstration was designed to afford accurate flow measurement while maintaining advantages of virtually zero head loss, operation under submerged, back flow, or surcharge conditions, and installation conditions not requiring significant construction. Furthermore, the ultrasonic sensors are free of significant intrusions and accordingly are not subject to fouling, damage by flow and do not cause flow blockage. The approach taken involved a new technique using integrated ultrasonic measurements of velocity and level and resulted in a practical, low cost system suited to wastewater characteristics and the operating environment of the sewage system. The design of the equipment was specifically adapted to the application, involves no moving parts, was shown to be suitably rugged and non-fouling, and easily installed in existing sewers with manhole access.

In its basic form the metering concept is quite simple. A beam of ultrasonic energy is directed through the sewage transport media in such a manner as to permit the determination of the average of the stream velocities along the beam. (It is shown that with proper placement and under reasonable conditions this average path velocity is nearly equal to the average of the stream velocities taken over the entire flow cross section.) A separate beam of ultrasonic energy is directed down through the air toward the surface of the sewage transport media and its echo detected, permitting an accurate determination of the depth. The depth (which is directly related to the flow cross section) and average velocity are then functionally combined to yield flow volume per unit time.

#### OBJECTIVES

The following five objectives were set for the demonstration before it began:

1. The key objective of the project is to demonstrate the performance of new sewage metering equipment which is of sufficiently low cost, to achieve general use, which can be conveniently installed in existing sewers, which requires minimal maintenance and is suited by design to long term operation in the sewer environment.
2. Verify the performance, design, installation and operation of an ultrasonic sewage meter by equipping and monitoring two existing sewers in the Milwaukee Sewerage System, one 12 feet in diameter and the other 5 feet.
3. Compare the performance of the ultrasonic meter, with respect to flow reproducibility and ease of installation with other metering devices presently installed in the system, electromagnetic metering in the case of the 12 foot diameter conduit and float/Kutter formula metering in the 5 foot channel.
4. Characterize mathematically and by computer solution the relationships between average volume flow, level, chordal velocity, and

Reynolds Numbers for sewer channels of typical cross sectional configurations. Determine the discharge coefficient associated with the above relationships and determine the universality of the discharge coefficient for typical cross section configurations.

5. Provide manual, computer, and automatic techniques for calculating and displaying average sewage volume flow (rate and quantity).

#### THEORETICAL APPROACH

The general concept of the unique metering system was advanced earlier. In the following, the principle of operation of each major element of the system will be explained. These are the velocity meter, height gauge and the electronics which combine the velocity and height information.

##### Velocity Meter

As pictured in Figure 1, two ultrasonic transceivers are affixed to the pipe wall, one upstream from the other. Pulses of ultrasonic energy are generated by one transceiver and received by the other. These pulses have the shape of a wave packet as shown in Figure 2 and are generated as the response of a piezoelectric crystal to a spike of input voltage. The voltage spike causes a momentary mechanical construction of the crystal. The crystal then vibrates to rest at its natural frequency which is in the ultrasonic range, selected for this project to be 400 kHz. The pulse generated thereby propagates through the liquid across the pipe to the other transceiver. When the pulse reaches the receiving crystal, it generates an output voltage waveform also shaped much like that shown in Figure 2. In operation, a received pulse electronically triggers the generation of another transmitted pulse in a "sing-around" fashion, creating a self-sustained pulse frequency,  $f$ . If electronic delays are small, the period of this frequency is just the time required for an ultrasonic pulse to travel through the fluid from transceiver to transceiver. If the distance across the pipe between the



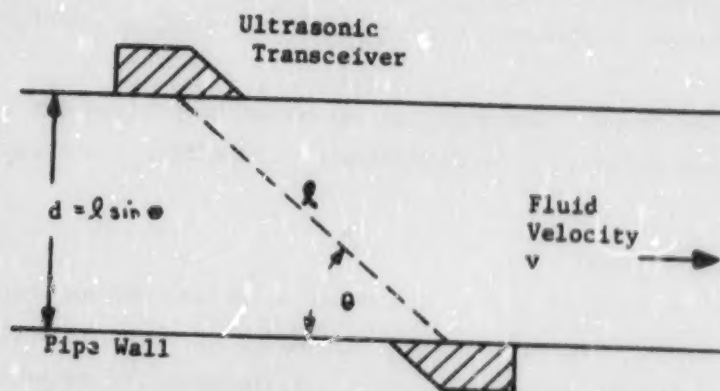


Figure 1. Ultrasonic Pulse Propagation Path Between Transceivers

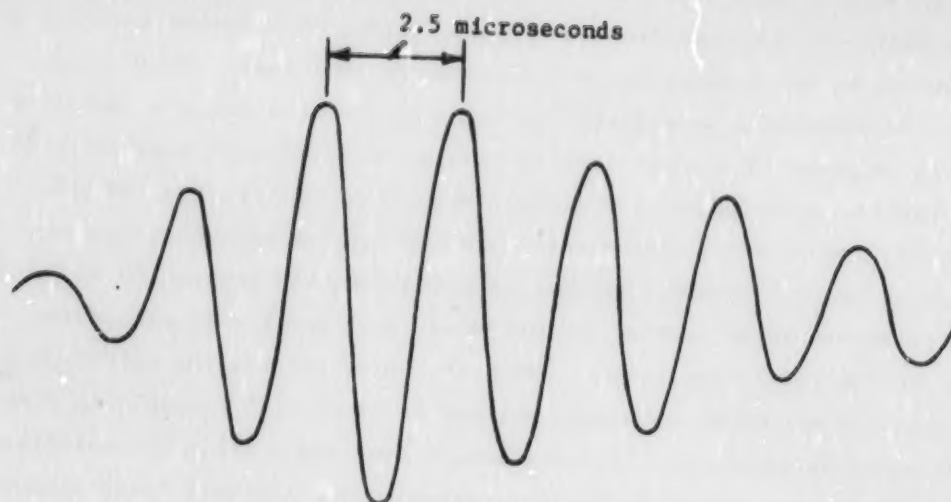


Figure 2. Wave Shape of Ultrasonic Pulse

transceivers in Figure 1 is  $l$ , and the velocity of sound in the metered liquid is  $S$ , travel time  $t$  is given by  $l/S$ . For fluid at rest, this travel time is the same for pulses moving in either direction. However, if the fluid is in motion, then the travel time  $t_d$  for pulses moving downstream is shortened because their transit is aided by the fluid motion and,

$$t_d = \frac{l}{S + \bar{v}_c \cos \theta} \quad (1)$$

where  $\bar{v}_c$  is the average fluid velocity along the transmission path or chord between the transmitter and receiver, and  $\bar{v}_c \cos \theta$  is the component of  $\bar{v}_c$  in the direction of pulse propagation. Pulses moving upstream travel more slowly because their transit is opposed by the fluid motion, thus the upstream travel time,  $t_u$ , is

$$t_u = \frac{l}{S - \bar{v}_c \cos \theta} \quad (2)$$

Assuming negligible electronic delays, the related sing-around frequencies are the inverses of their respective transit times, or

$$f_d = \frac{S + \bar{v}_c \cos \theta}{l} \quad (3)$$

$$f_u = \frac{S - \bar{v}_c \cos \theta}{l} \quad (4)$$

Flow velocity information is provided by the difference between these frequencies:

$$\Delta f = f_d - f_u = \frac{2 \cos \theta}{l} \bar{v}_c \quad (5)$$

In any given installation,  $\theta$  and  $l$  are constants, thus  $\Delta f$  is proportional to the average fluid velocity along the line joining the transceivers.

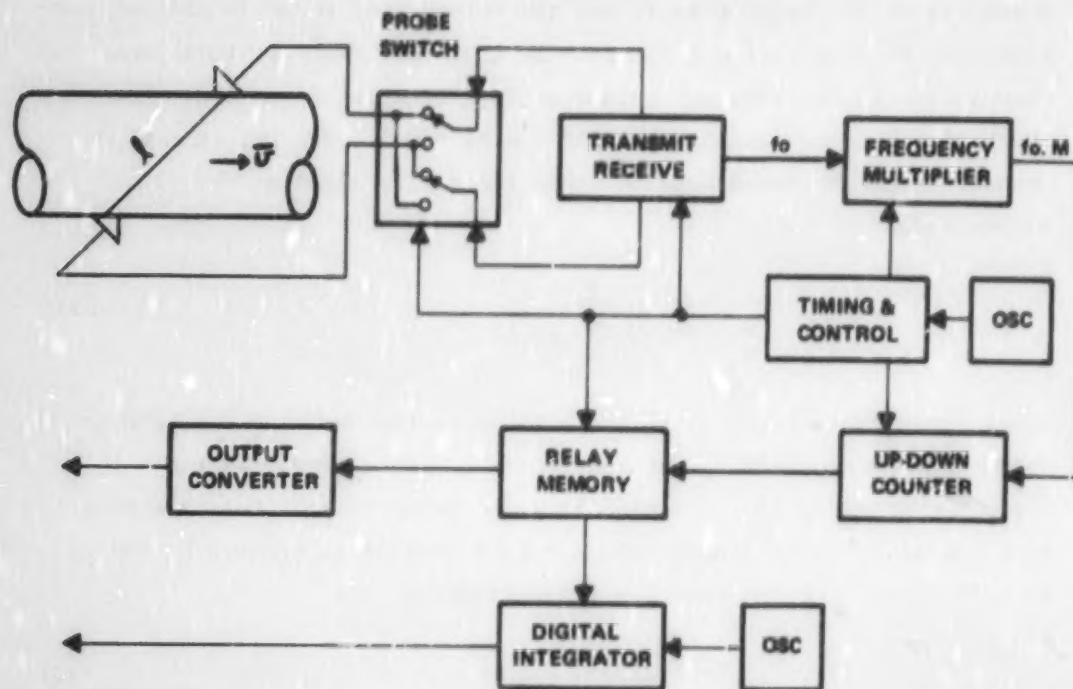


Figure 3. Block Diagram of Meter Electronics

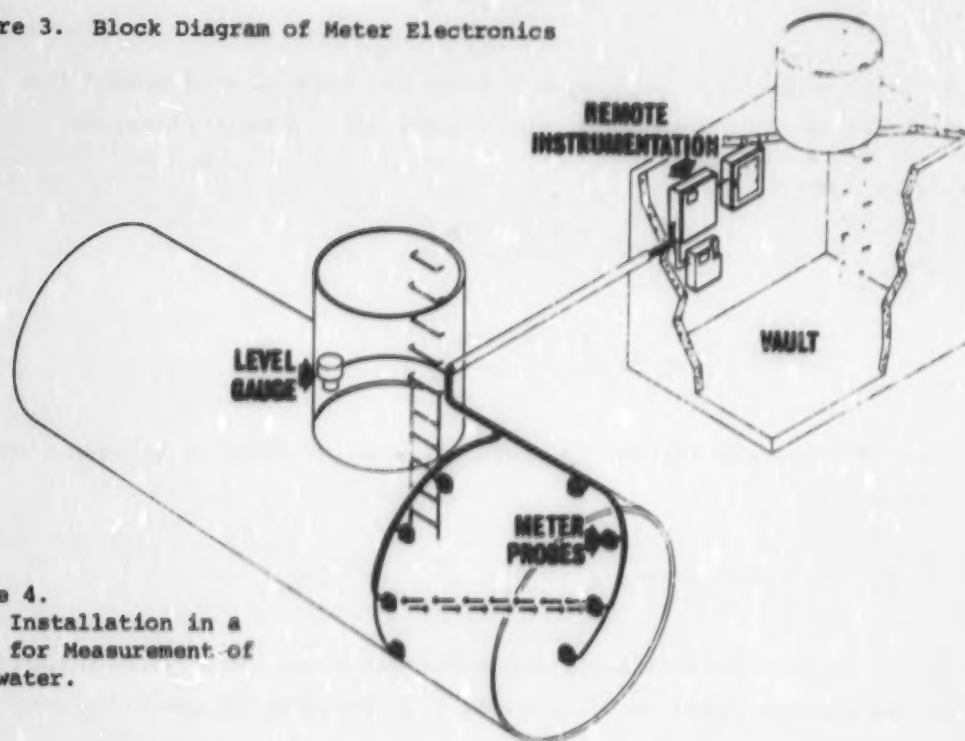


Figure 4. Meter Installation in a Sewer for Measurement of Wastewater.

As described in Appendix A (Velocity Profile Analysis), this average velocity along the ultrasonic beam crossing the pipe,  $\bar{v}_c$ , can be related to the average velocity,  $\bar{v}$ , across the entire flow cross the entire flow cross sectional area if flow is in either the laminar or turbulent regimes.

In practice, the  $\Delta f$  of equation (5) is a very small number, too small to be measured directly with much precision. For example, the velocity of sound in water is about 1500 meters per second, and in a pipe one meter in diameter carrying water flowing 2 meters per second, this frequency difference is:

$$\Delta f = f_d - f_u = 563.195 - 561.805 = 1.39 \text{ Hz} \quad (6)$$

where  $\theta$  is taken as  $22^\circ$ .

For this reason, each sing-around frequency is multiplied by a constant  $M$  which is usually about 100. For  $M = 100$ ,  $\Delta f$  becomes 139 Hz in this case. In operation, the meter measures  $\Delta f$  by counting  $f_d$  for a period  $t_c$ , and counting  $f_u$  for a like period and subtracting the two counts. This count difference  $\Delta N$  is proportional to  $\Delta f$  and is given by

$$\Delta N = M \Delta f t_c = \frac{M 2 \cos \theta}{L} \bar{v}_c \quad (7)$$

Taking  $t_c$  as 2.5 seconds, for the above example,

$$\Delta N = 100 (1.39) (2.5) = 327.5, \quad (8)$$

and  $\Delta N$  is sufficiently large to be measured easily with good precision.

Electronic Signal Processing - With the probe switch in the position shown in Figure 3, the upper transceiver is transmitting pulses upstream and the lower transceiver is receiving ultrasonic pulses from the stream. The generated sing-around frequency is  $f_0$  if there is zero flow and  $f_u$  if there is flow in the direction shown. The frequency multiplier multiplies



the frequency by  $M$ . An oscillator generates a clock rate for the timing and control circuits, these in turn provide various multiples of the clock rate for controlling the probe switch and resetting the frequency multiplier and up-down counter. The probe switch is reversed every  $t_c$  seconds, thereby reversing the roles of the transceivers and alternately generating  $f_d$  and  $f_u$ . During each such cycle, the up-down counter counts up to  $Mf_d$  and then counts back down to  $Mf_u$ . The number remaining in the counter after such a cycle is the  $\Delta N$  defined in equation (7) and is proportional to  $\Delta f$ . The value of  $\Delta N$  is stored in the relay memory after each cycle until it is updated by the next measurement cycle. For  $t_c$  equal to 2.5 seconds, the count stored in the relay memory is updated every five seconds. In digital binary format in the memory, the count is converted to an analog output current proportional to flow rate by means of a seven element ladder circuit in the output converter. The clock rate from the oscillator is digitally multiplied by the binary number in the relay memory representing flow rate and sent to an eleven element binary counter in the digital integrator. Elements of this counter can be "strapped" in or out of the counting sequence so as to scale the integrator output to convenient engineering units of quantity, i.e., cubic meters, gallons, acre, feet, etc. Similarly, binary elements in the frequency multiplier and relay memory can be strapped in or out to select the proper value for  $M$  and full-scale respectively.

#### Height Gauge

Conceptually this unit is much the same as the velocity meter except for the following: The burst frequency is about ten times lower (40 kHz), the burst repetition is preset to permit the reception of the echo from the greatest distance desired (generally the bottom if and when the channel is empty), differences in the sonic velocity of air are corrected for by monitoring the air temperature and making an offset linear correction to the echo time measurement and a single transmitter-receiver head is used. This transceiver unit is placed several feet up

the manhole to minimize chances of fouling during surcharging. Any echo time shorter than that expected for a full conduit (such as would occur during surcharging) is interpreted the same as that received when the conduit has just reached its 'full' point.

The combined height gauge and velocity meter system is shown in a sketch (Figure 4) of one of the sewer installations carried out as part of this demonstration. It is important to understand that although four sets of velocity transmitter-receiver probes are shown, only one such set is required in a typical installation. The extra sets were installed as a means of verifying the validity of using a single transverse velocity average to represent the average velocity of the entire flow cross section. (The validity of this procedure is discussed at length in Appendix A.)

#### Velocity-Height Combination

For a circular conduit, the relationship between depth (d), radius (r) and flow cross-sectional area (A) is given as

$$A = \pi r^2 \left\{ \frac{1}{2} + \frac{1}{\pi} \left[ \sin^{-1}(x) + x \sqrt{1-x^2} \right] \right\} \quad (9)$$

where x is given as  $(d/r-1)$ .

Although the height gauge provides a measurement which is actually proportional to the 'distance-to-product', this can be translated using a digital electronic scheme to be proportional to the flow cross-sectional area A. A voltage proportional to this area is then used as the supply voltage for the binary ladder in the relay memory. The output of the relay memory is thus proportional to the product of the average transverse velocity  $\bar{v}_c$  and the flow cross section area A.

Average transverse velocity versus average area velocity - For the case of a circular conduit running full, the flow velocity  $v$  at any point on the logarithmic velocity profile associated with turbulent flow at a distance  $x$  from the axis of the pipe of radius  $R$  is

$$v = v_{\max} + 2.5 v^* \ln \frac{R - x}{R}, \quad (10)$$

and

$$v^* = \bar{v} \sqrt{\frac{\lambda}{8}} = \text{"friction velocity"} \quad (11)$$

where  $\lambda$  = pipe friction coefficient

Using (11) and integrating,

$$\bar{v} \frac{1}{\pi R^2} \int_0^R v 2\pi x dx = v_{\max} - 3.75 v^* \quad (12)$$

$$\bar{v}_c = \frac{1}{R} \int_0^R v dx = v_{\max} - 2.5 v^* \quad (13)$$

Therefore:

$$\bar{v} (1 + 3.75 \sqrt{\frac{\lambda}{8}}) = v_{\max} \quad (14)$$

and

$$\bar{v} = \frac{v_{\max}}{1 + 3.75 \sqrt{\frac{\lambda}{8}}} \quad (15)$$

Dividing  $\bar{v}$  by  $\bar{v}_c$  yields:

$$\frac{\bar{v}}{\bar{v}_c} = \frac{1}{1 + 0.44194 \sqrt{\lambda}} = k. \quad (16)$$

The pipe friction coefficient  $\lambda$  is generally between 0.01 and 0.06 so, for a full pipe on a major chord,

$$0.9023 < k < 0.9577 \quad (17)$$

depending upon the value of  $\lambda$ .  $k$  is the constant by which  $\bar{v}_c$  must be multiplied to yield  $\bar{v}$ .

Since a similar equation does not exist for partially full circular conduits, it was necessary to examine experimentally obtained data for such conduits to determine the  $k$ -factor ranges. The reduction of this data for partially full circular pipes has indicated that a value of  $k$  of 0.96 is typical over a significant portion of the cross section when chordal velocity averages are obtained for planes parallel to the surface plane and between 30% and 70% of depth. (This is presented in more detail in Appendix A.) The constant  $k$  is incorporated into the scaling electronics along with the scaling multiplier for engineering units and the cross section area multiplier for calculation of  $Q$ . In general:

$$Q = A\bar{v} = Ak\bar{v}_c \quad (18)$$

These constants are taken into account when the electronics are set up for a particular installation. The adjustments are made by appropriate strapping of elements in binary counting chains and are accomplished by either soldering or not soldering jumpers in the standard unit.

The applicability of the above  $k$ -factor for calculation of  $Q$  depends upon the existence of a fully developed velocity profile of a reasonably predictable form. The transceiver mounting site should therefore have 10 to 20 straight diameters upstream and be sufficiently distant from elbows, constrictions, expansions and pumps. When these



criteria are met, the calibration has been shown to be adequate and accurate.

Electronic output - the electronic unit pictured in Figure 5 contains all of the digital signal processing circuitry mounted on individual plug-in printed circuit cards, as well as the power supplies and data readout equipment. The level unit provides a 0-10 volt signal proportional to the distance to the surface. This signal is processed in the velocity electronic unit to provide the voltage  $V_a$  proportional to the fluid cross section area. The flow signal, generated in the velocity electronic unit is a 4 - 20 mADC output current proportional to flow rate. The output signal generated by combining the velocity and area signals is suitable for telemetering and driving remote readout equipment. Circular and strip chart recorders, magnetic and punched paper tape recorders, and remote totalizers can be provided for this purpose.

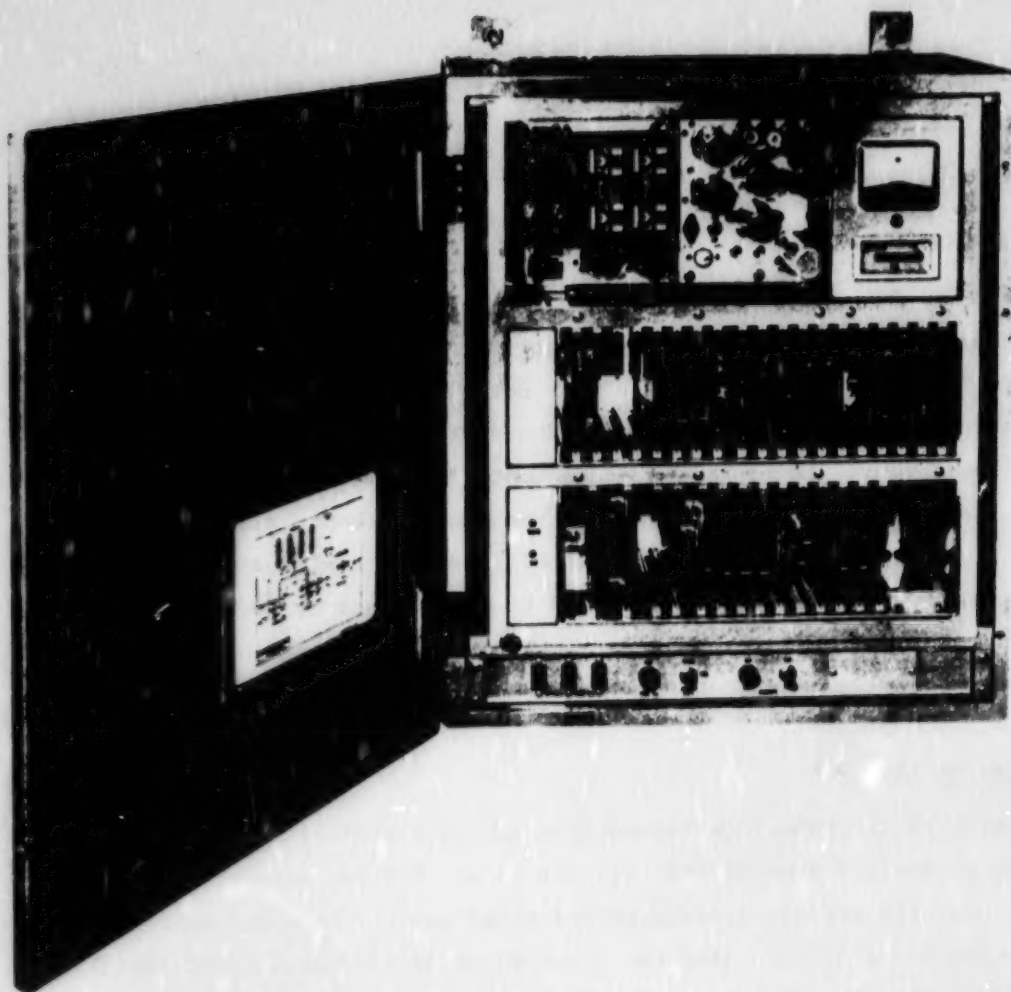


Figure 5. Meter Electronics Unit

## SECTION IV

### INSTALLATION

#### SITE LOCATIONS

Two sites were initially selected as representative combined storm-sanitary sewers. These were the Cambridge Avenue Site located near the village of Shorewood in the near north metropolitan Milwaukee area, (see Figure 6) and the South Shore Plant Site on the far south-southeast side. Later in the demonstration project the College Avenue Site was selected. This third location was upstream a mile or so from the South Shore Site and eliminated difficulties experienced due to abnormally high loadings contributed by a glue factory located next to the South Shore Treatment Plant. (This is discussed in detail later in the report.)

#### Cambridge Avenue

A sketch of the Cambridge Avenue Site was used earlier (Figure 4) as being typical of a meter installation in an existing sewer (except that only one set of velocity probes would usually be required). This location has a 60 inch diameter circular conduit located approximately 30 feet below the surface. (See Figure 7). The metering site is 1202 feet downstream from an existing weir and float type monitor, 542 feet downstream from the junction with another smaller sewer and about one-third mile upstream from the junction with an inverted siphon. It is known that at times of high flow, some back-watering and surcharging does occur due to the inverted siphon, and hence the validity of the measurements based on level only would be suspect. Head diagrams for the vicinity of this site are included as Figure 8. A flow record, based on the weir and float data located upstream of the ultrasonic metering site, as well as the 39 inch East Providence Street sewer

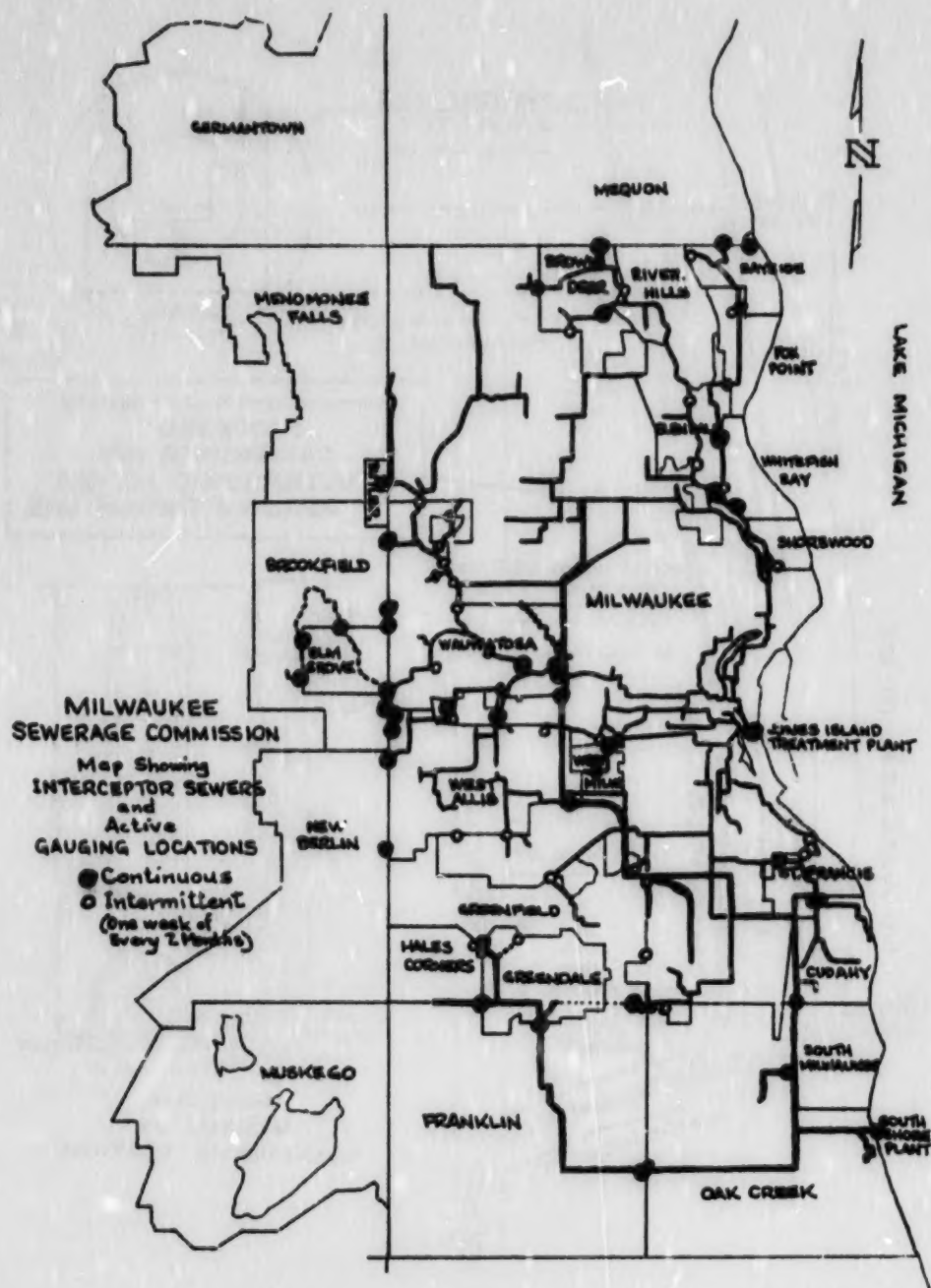


Figure 6. City of Milwaukee Sewerage System Map



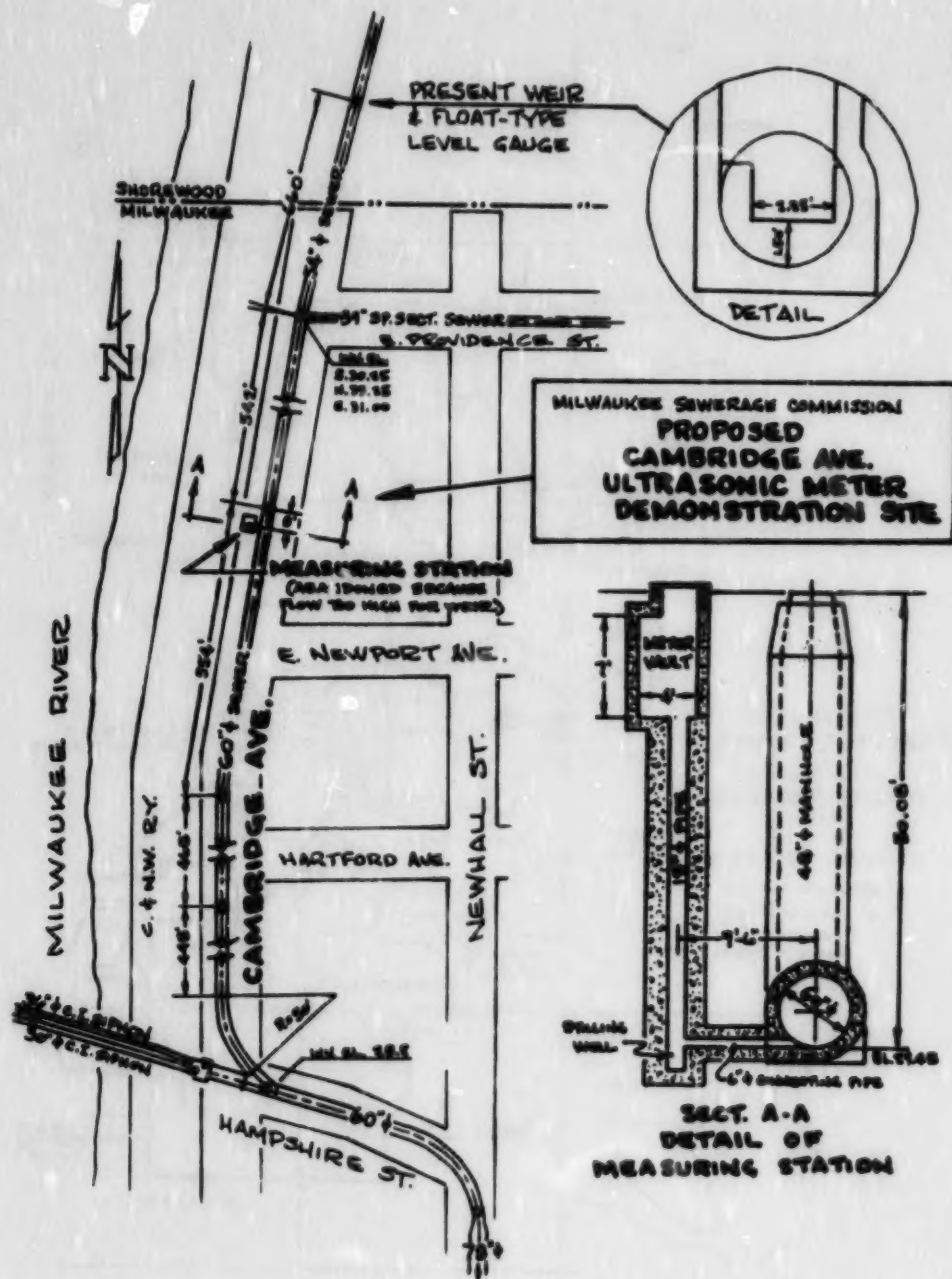


Figure 7. Location and Configuration of the 60" Cambridge Avenue Sewer

MILWAUKEE SEWERAGE COMM. INTERCEPT SEWERS  
IN THE VICINITY OF THE CAMBRIDGE AVE. ULTRASONIC  
METER INSTALLATION

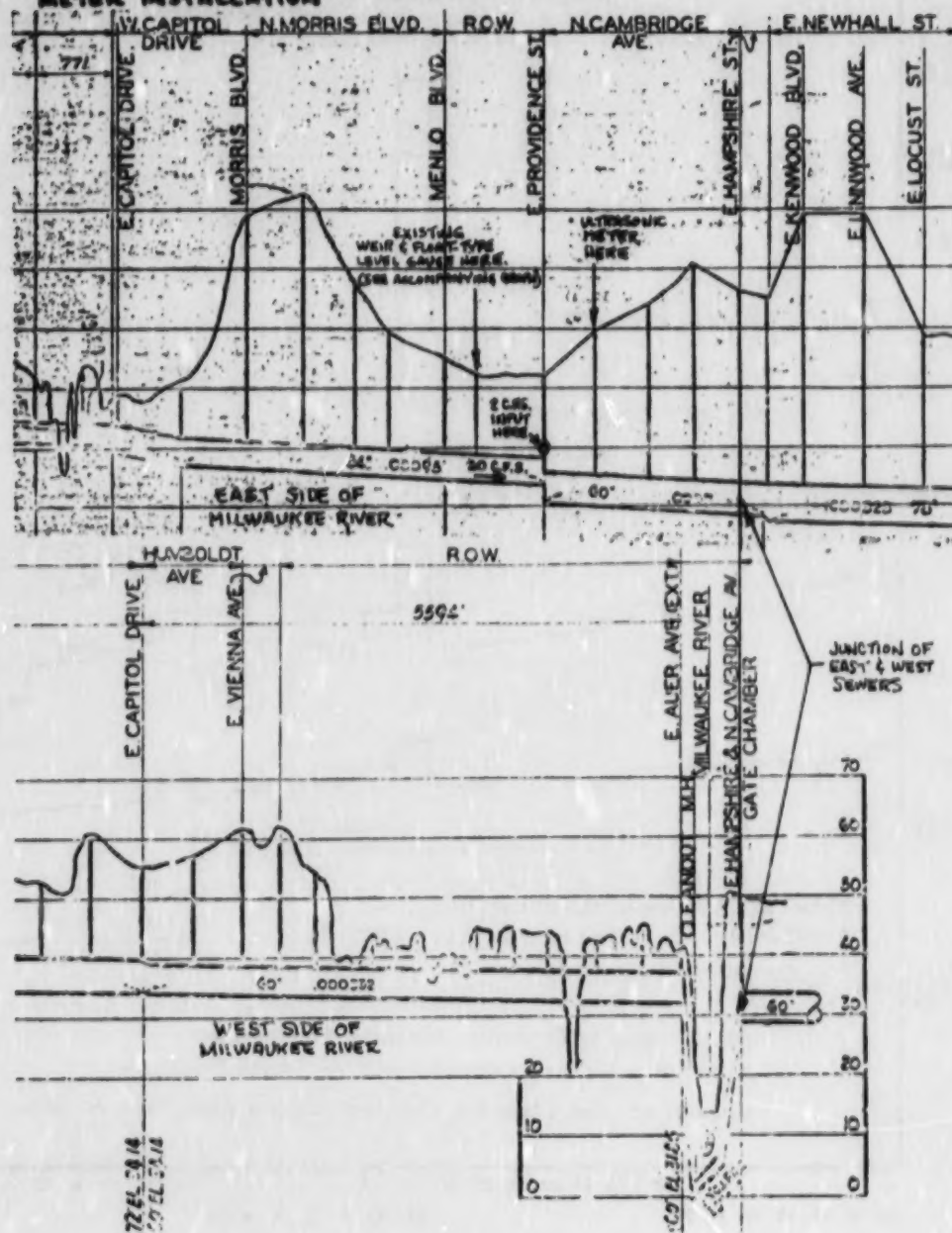


Figure 8. Head Diagram, Vicinity of Cambridge Avenue Meter Installation

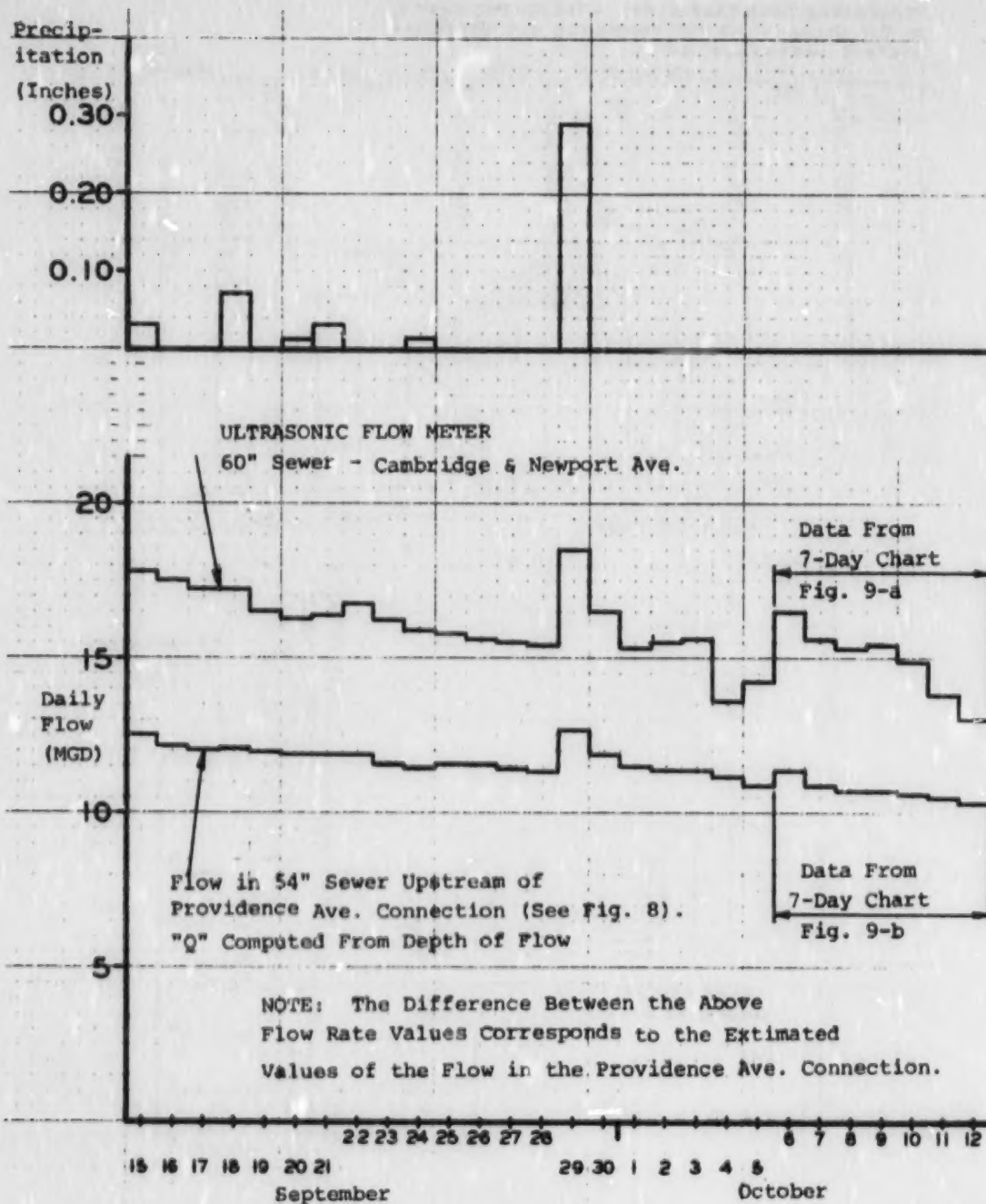


Figure 9. - Comparison of Measurements - Ultrasonic vs Level Only.

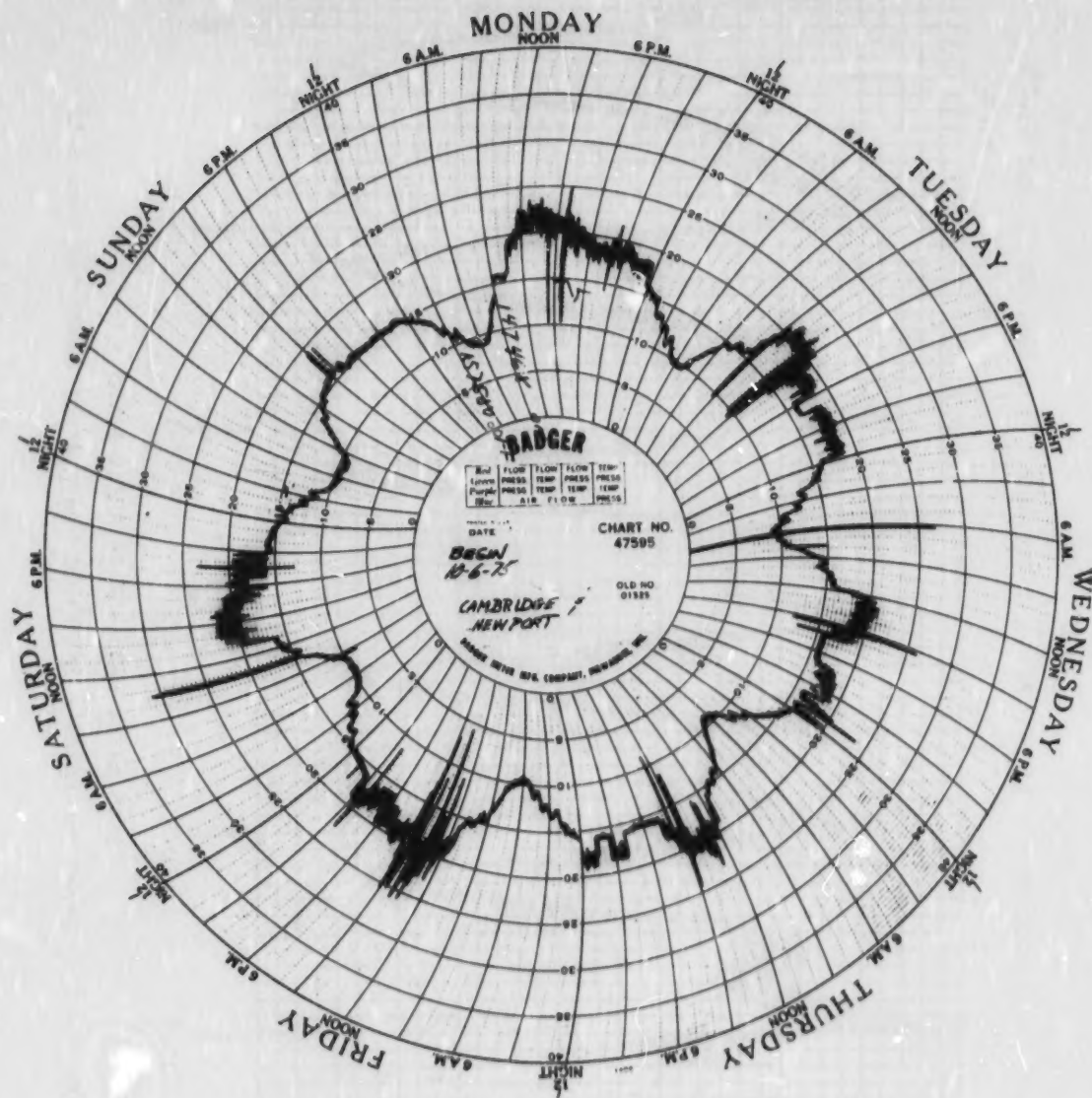
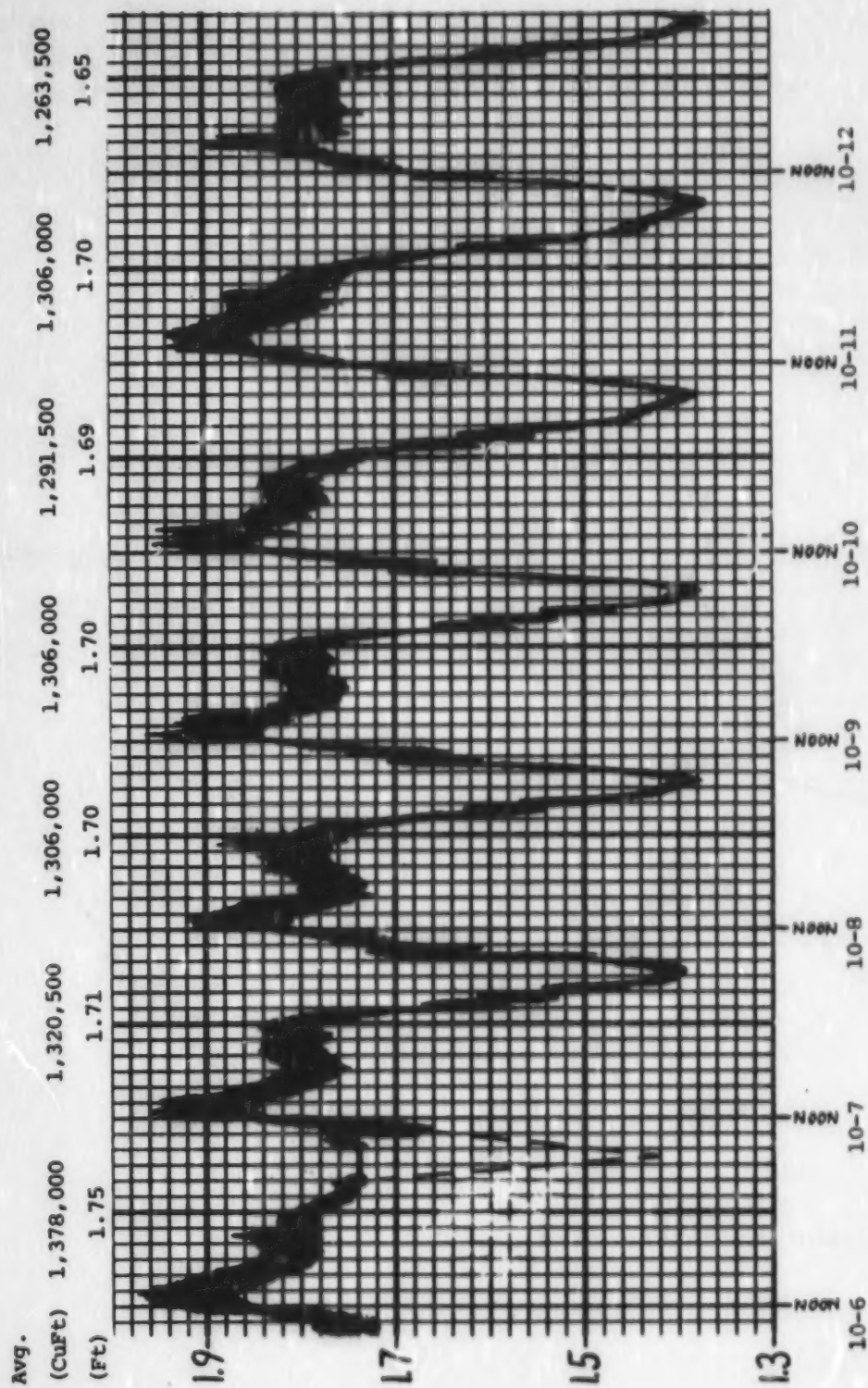


Figure 9a. Flow Recording - 60" Cambridge Ave. Sewer





8:45 AM/10-6-75 - 8:45 AM/10-13-75  
Figure 9b. Level Recording - 54" Sewer Upstream of Cambridge Ave. Site

outfall, is included as Figure 9. Two 7-day charts showing the ultrasonic flowmeter recording and flow upstream of the ultrasonic metering sites are included as Figures 9a and 9b respectively. Naturally these flow quantities would be somewhat lower than would be expected at the ultrasonic metering location since they do not include all flows which reach that site.

#### South Shore

A survey sketch of the influent channel at the South Shore Plant is shown in Figure 10. This is a 12.5 foot diameter circular conduit at the location of the velocity probe installation which is 60 feet upstream from the plant inlet section. A transition section begins 36 feet downstream. The height gauge transceiver was placed at the inlet bay so as to be more accessible and better protected in the event of surcharge. Mag meters are located downstream of the bar screens which are located immediately downstream from the inlet bay. It was anticipated that these would be used to assist in evaluating the operation of the ultrasonic system.

A profile drawing of the sewers in the vicinity of this site is shown in Figure 11. Note the proximity of the Peter Cooper Corporation (glue factory) outfall and drop pipe.

#### College Avenue

A detail of the manhole and sewer at College and Pennsylvania Avenues is shown in Figure 12. At this location the sewer is a 12 foot diameter circular conduit. The average depth of flow is 3 feet with a maximum depth of 8 feet noted following a heavy downpour in 1972.

#### INSTALLATION DETAILS

There are several ways in which the velocity probes can be installed in a sewer. On steel conduits, they can be clamped on externally.

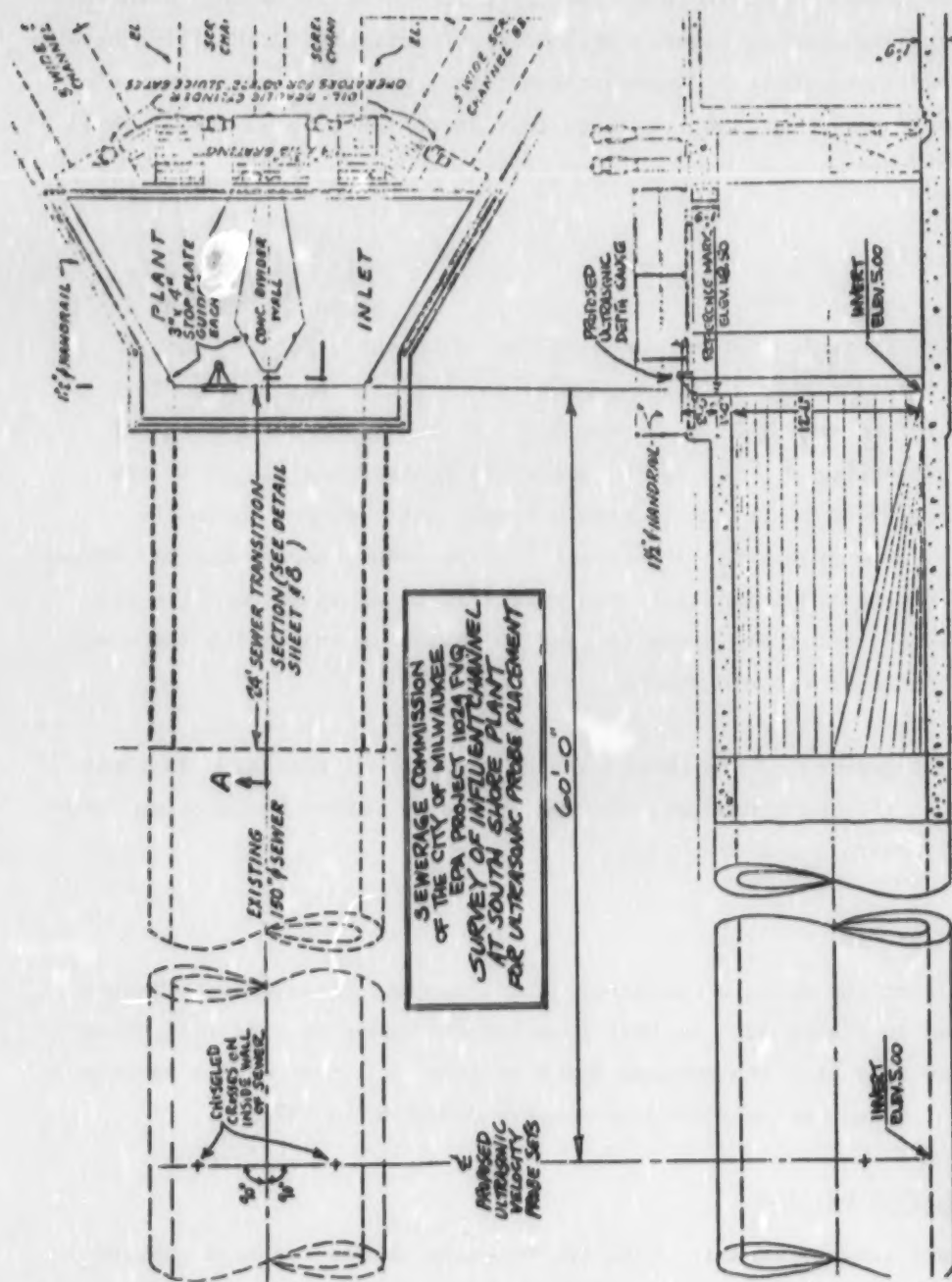


Figure 10. Location of Meter Installation, South Shore

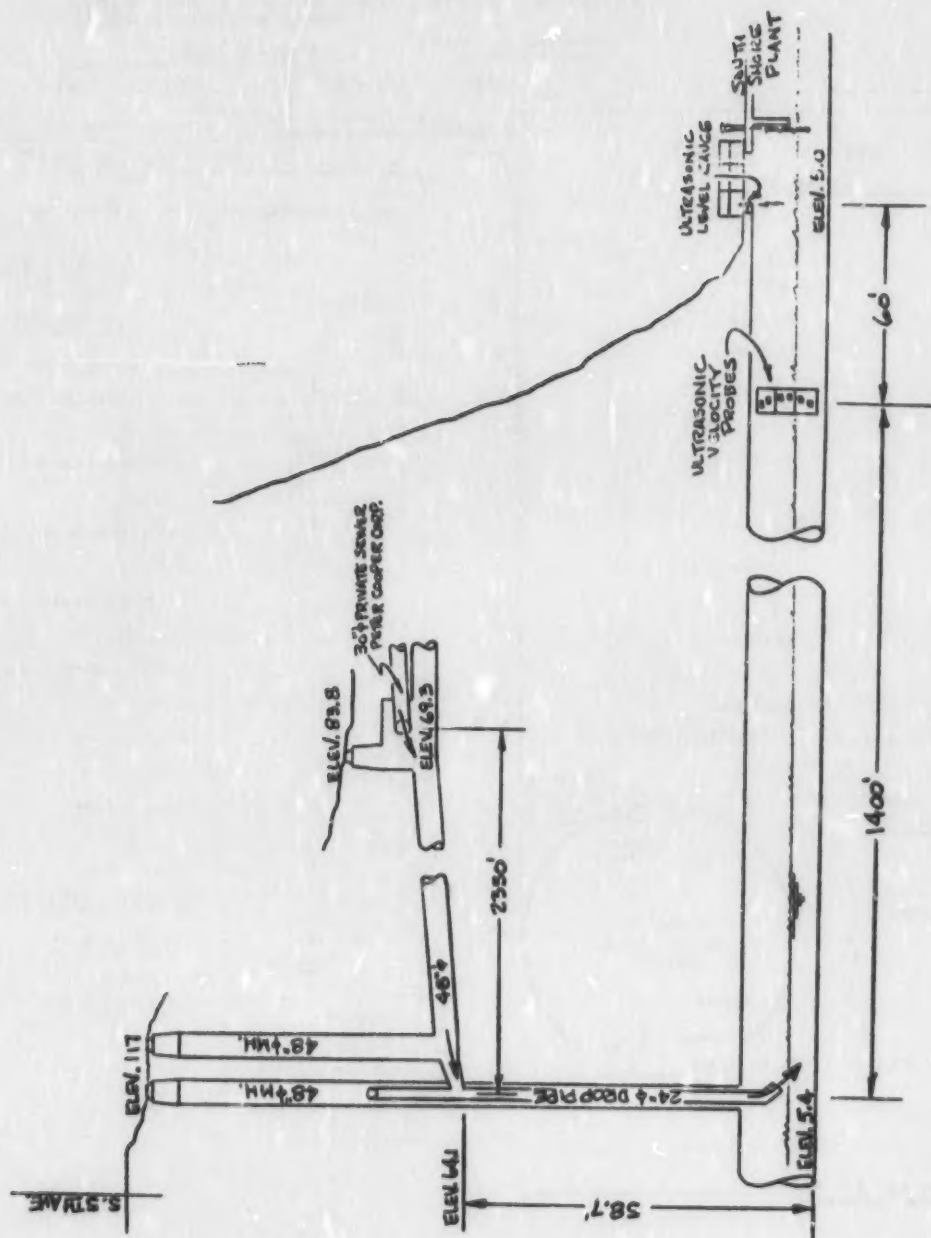
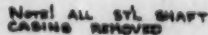


Figure 11. Profile of Sewers in the Proximity of South Shore Plant



PROPOSED INSTALLATION BY JUNE 1968



28

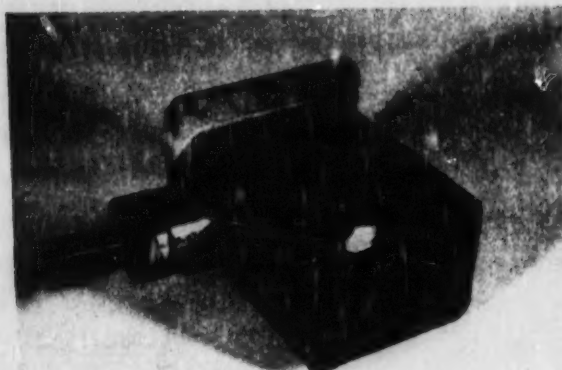


Figure 13. 400 kHz Ultrasonic Transceiver

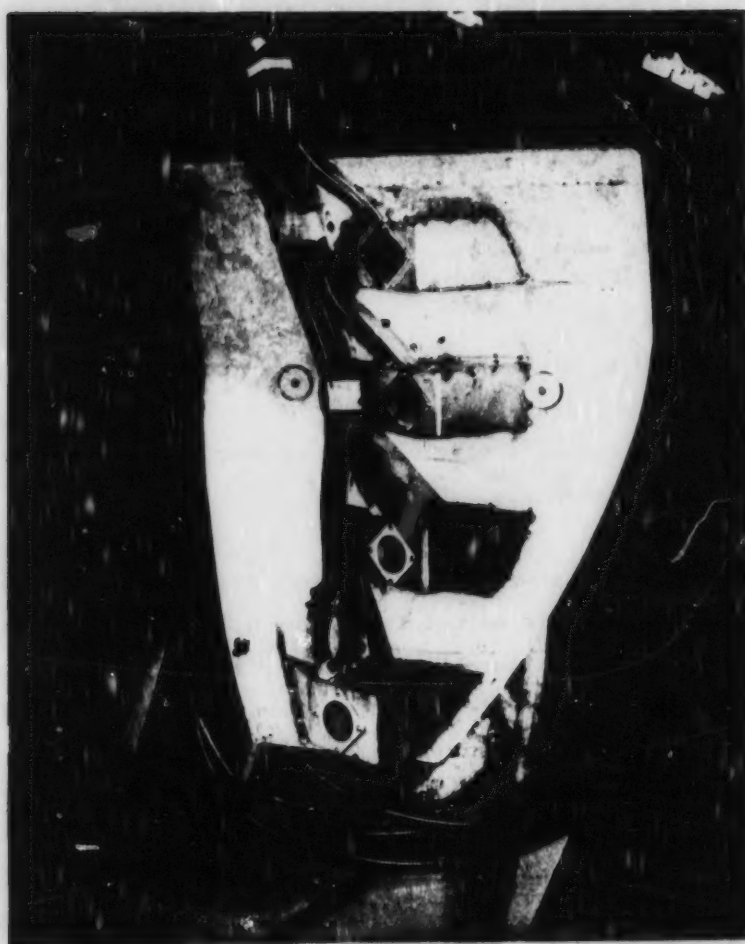


Figure 14. Multiple Probe Mounting Configuration

Where block-outs exist they can be installed flush with the inside surface. Finally, where neither of the first two methods are practical, they can be affixed to the inside of the conduit. Due to the site characteristics at all three locations this third technique was selected. Furthermore, to facilitate the alignment, the transceivers or probes were housed in hydrodynamic shields mounted on curved plates which were then affixed to the interior wall of the sewers. Typical fixtures are shown in Figures 13 and 14. Wires from the transceivers are carried to a junction box and then to the electronic unit. The spacing between the transceivers on the pipe is first calculated and then confirmed by both physical and electronic measurements, taking into account the propagation of the sound pulses through the plastic material encapsulating the transceiver crystal and through the metered liquid. The path angle through each medium is governed by the velocity of sound in each medium according to Snell's law:

$$\frac{\sin \theta_1}{S_1} = \frac{\sin \theta_2}{S_2} \quad (19)$$

where  $\theta_1$  and  $\theta_2$  are the path angles in the transceiver and the liquid respectively  
 $S_1$  and  $S_2$  are the velocities of sound in these respective media.

From a knowledge of the sewer dimensions and probe spacing, a zero flow sing-around frequency  $f_0$  is calculated. When the transceivers are fixed in place, the actual zero flow signal is measured and compared with the calculated value. If these two agree within 1%, the installation is judged satisfactory and the output readings correspond to actual flow. This procedure has been verified in a large number of actual installations.

For most sewer installations in the sizes commonly encountered (1 foot to 15 feet and larger) Reynolds numbers are well into the turbulent range.

Installation diagrams for each of the sites are shown in Figures 15 (Cambridge Avenue), 10 (South Shore) and 16, 17 and 18 (College Avenue). It should be noted that the two probe sets used at the College Avenue Site were the top two sets (of six sets) from the South Shore Site.

The height gauge at College Avenue was also obtained from the South Shore Installation. Note that the level sensor was not positioned directly over the sewer center line since it was necessary to mount the sensor in the manhole (see Figure 16). This was judged to be satisfactory since the flow level is never so low as not to present an adequate reflective surface directly below the level sensor.



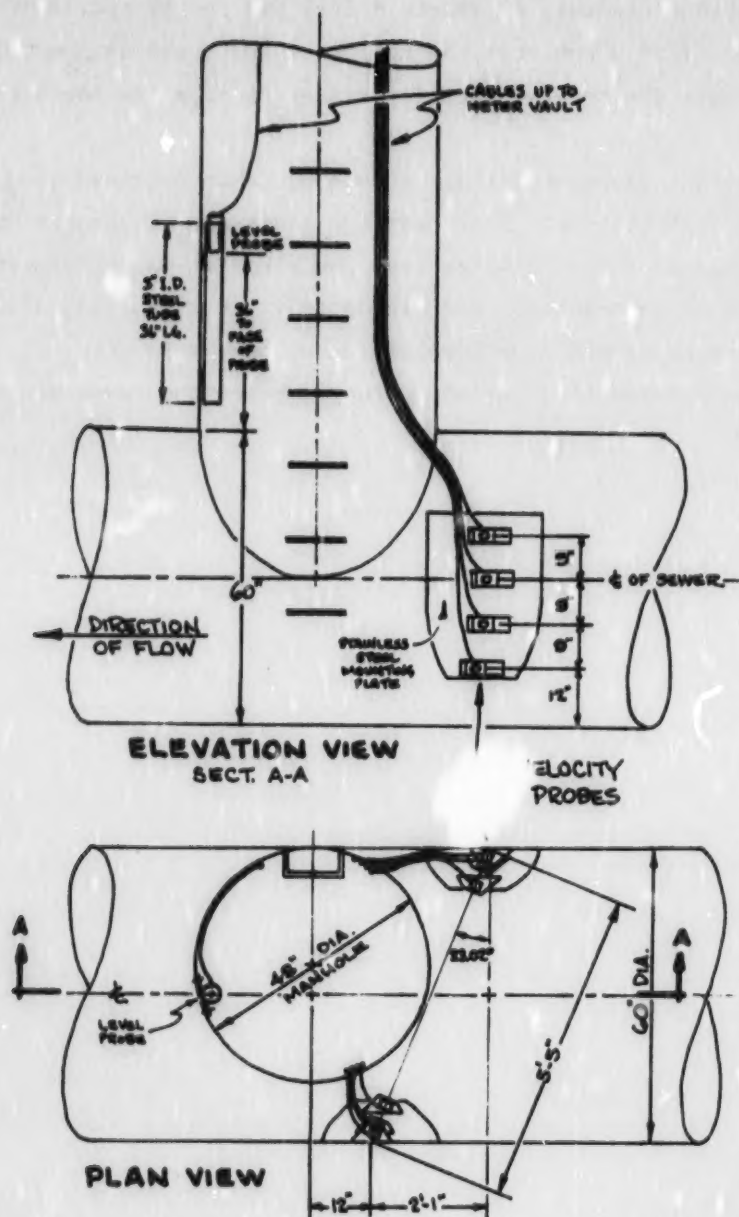


Figure 15. Ultrasonic Probe Mounting Configuration, Cambridge Avenue

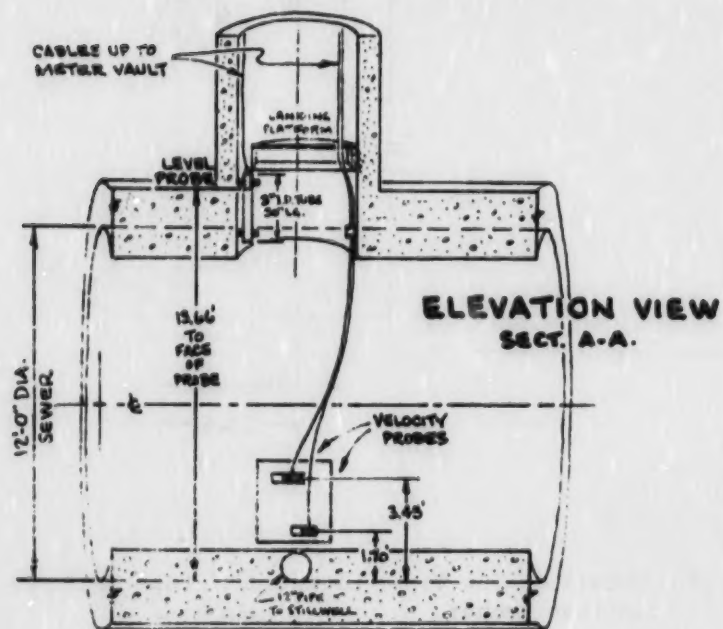
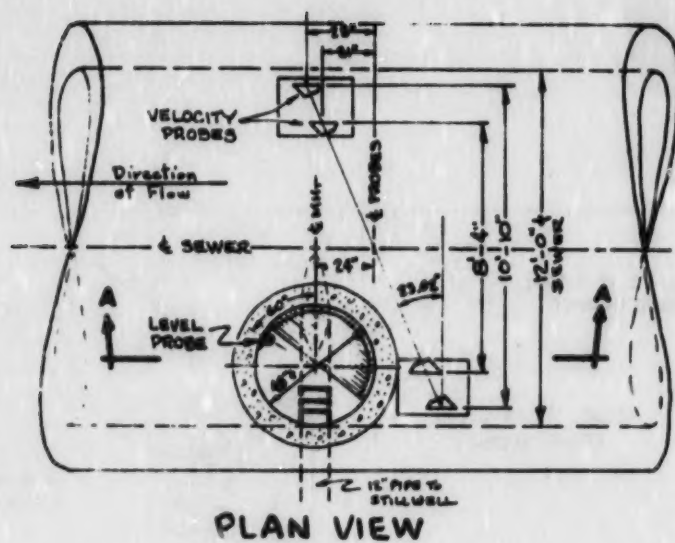


Figure 16. Ultrasonic Probe Mounting Configuration, College Avenue

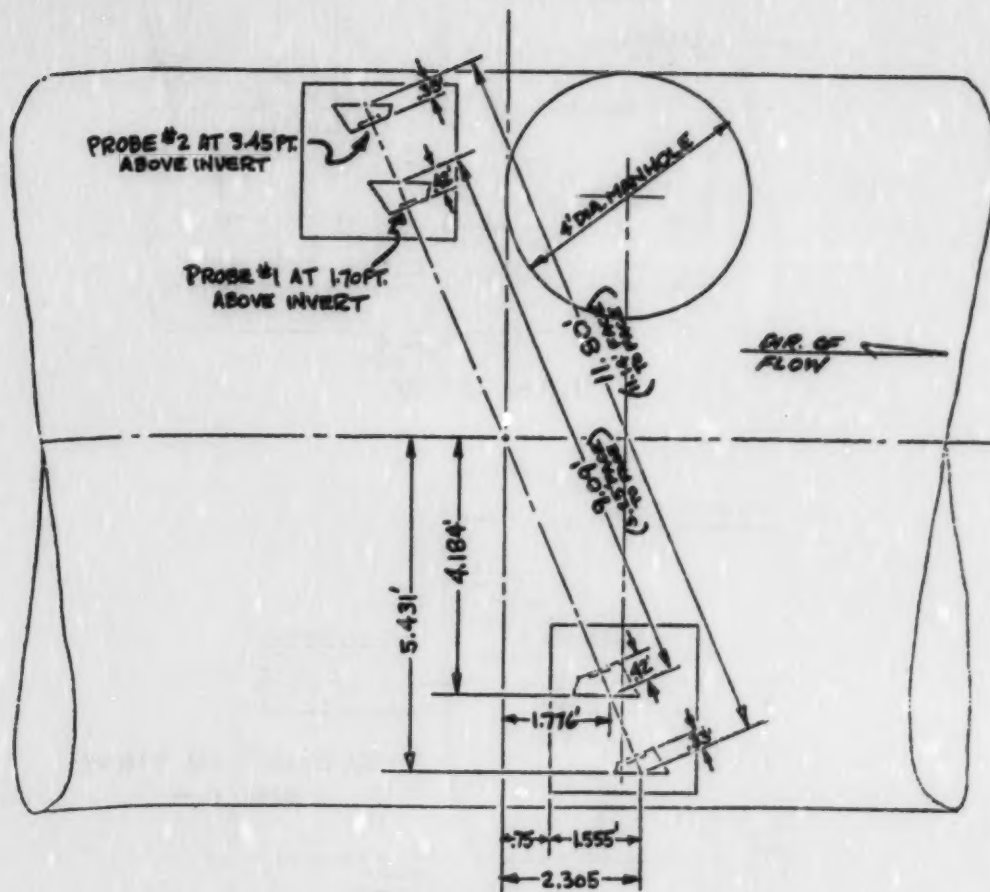


Figure 17. Detailed Plan View, Ultrasonic Probe Mounting Configuration, College Avenue

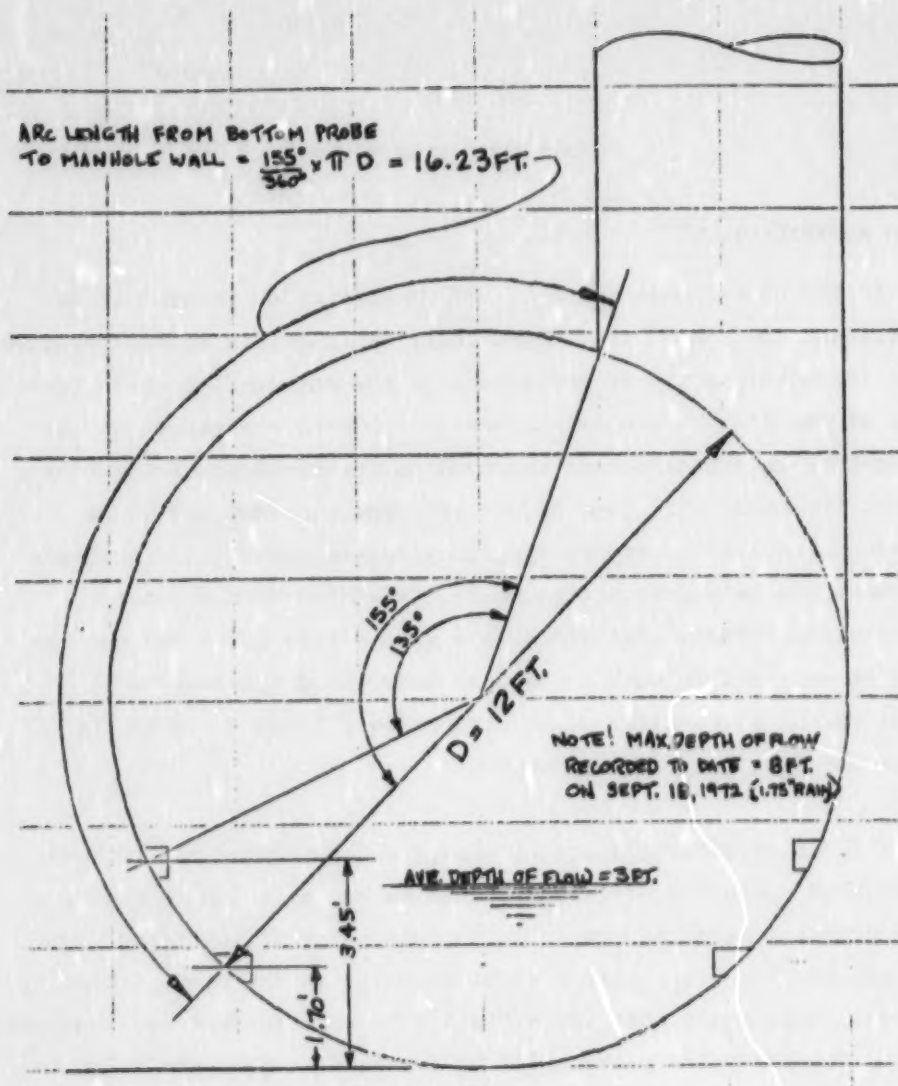


Figure 10. View Looking Upstream, Ultrasonic Probe Installation,  
College Avenue



## SECTION V

### OPERATION & EVALUATION

#### DESIGN MODIFICATIONS

Early in the operational phase of the demonstration program it became evident that there were significant fluctuations in the received signal strength, caused by variations in the attenuation characteristics of the fluid transmission medium. Due to the nature of the Leading-Edge detection scheme employed in the receiver-transmitter block of the basic unit (see Figure 19), these random amplitude variations resulted in random frequency modulations of the upstream and downstream sing-around frequencies generated by the Astable Multivibrator (ASMV). Occasionally a transmitted pulse was not received at all, and in such a case the ASMV would time-out to its natural period termination point, injecting a large error in the sing-around frequency determination.

The difficulties with utilizing Leading-Edge detection can be seen by examining again the ultrasonic pulse packet as shown in Figure 20. If the detector level is set so as to detect any voltage excursion which exceeds level  $V_1$ , then a received pulse is detected at time  $t_1$ , as shown. This means that for a fluid with both uniform and constantly homogeneity each pulse packet will be detected at the same point in time within the packet. However, should the packet shown be attenuated by 50% on occasion, the pulse packet would not be detected until time  $t_2$ . This injects a time error of about 2.5 micro-seconds into the determination of the sing-around period (see Figure 20). In the installations being tested this could amount to more than a full scale error in the determination of channel velocity, depending entirely on the random nature of the amplitude fluctuations.



Figure 19. Basic Unit, Receiver-Transmitter

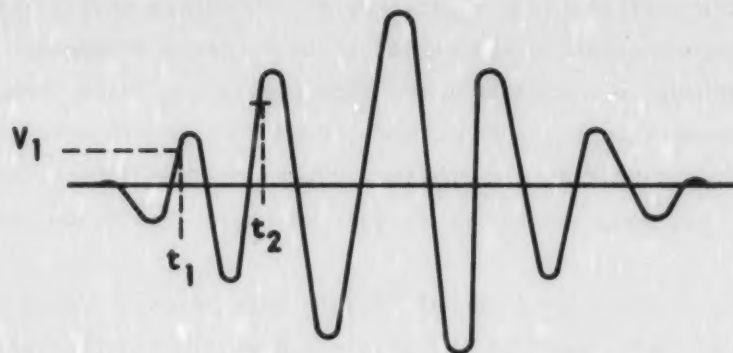


Figure 20. Ultrasonic Pulse Packet

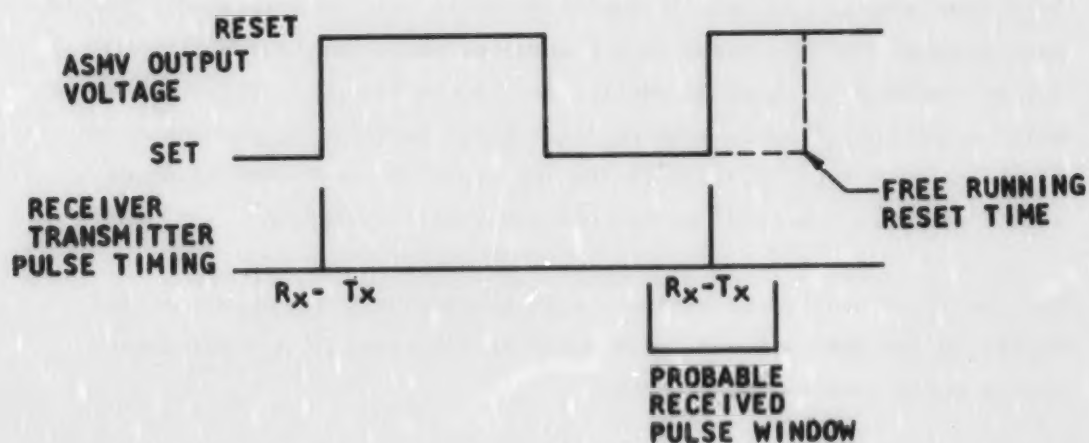


Figure 21. Timing Diagram

The difficulties with triggering the ASMV and transmitter directly upon detection of a received signal becomes apparent upon examination of the ASMV function. The timing diagram shown in Figure 21. Note that the free-running period of the ASMV is so set that it is in a resettable mode well before the time range in which a received pulse might occur, and will reset itself automatically well after the probable received pulse time range. Since the transmitter is fired upon reset of the ASMV, the self-starting capability of the entire unit is ensured. However, should a received pulse packet be so severely attenuated so as not to be detected, an extremely large time error, and hence frequency error, is injected into the system, and indeed such errors were observed. It was thus obvious that an alternative to Leading-Edge detection was necessary and that some substitute trigger mechanics had to be provided.

Close study and evaluation of the ultrasonic pulse packets being received indicated that, although the sewage medium did randomly attenuate pulse packets in varying amounts, all oscillations within any one packet were generally attenuated by the same amount. Consequently, it was determined that detection of the peak of the pulse packet envelope would provide more stability. Using this scheme, relatively rapid fluctuations in the envelope would not be detrimental and by adding automatic gain control (AGC) long time constant changes in amplitude could also be tolerated. The AGC also ensured that the pulse packet envelope would not have a slipped top due to over-driven receiver amplifiers. Since the pulse packet envelope existed for only 1% of the total "listening" period, the AGC had to be of the "keyed" type, i.e., only the amplitude of the packet envelope itself would be "checked" to determine any gain correction.

The remaining problem of automatically triggering the transmitter and resetting the ASMV without undue delay in the event of a missing received pulse involved more effort.

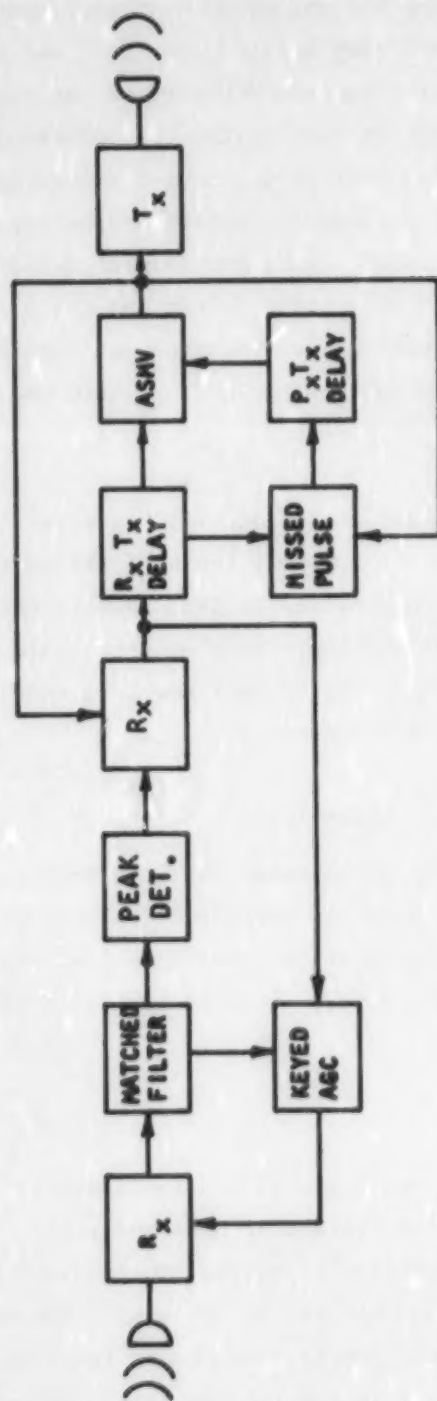


Figure 22. Modified Unit, Receiver-Transmitter



In this case an analog scheme was employed in which a ramp voltage was generated at the time the ASMV entered the "set" mode and the voltage which existed at the time at which a pulse was received was held. During the next cycle the ramp voltage was compared to the value held and if it exceeded that value, caused a surrogate trigger to be injected. To ensure an adequate capture capability in the event of a reduction in the sonic velocity, a small delay was inserted between the detection of a pulse packet and the triggering of the transmitter. Additional noise rejection was obtained by blanking the receiver detector during the period for which the ASMV was in the "set" mode.

The block diagram of the stages in the modified receiver transmitter block is shown in Figure 22. Laboratory tests of the modified system under ideal conditions resulted in less than 1% error when 9 out of 10 pulses were absent and there were no detectable effects when the input signal amplitude varied over the full range allowed by the receiver gain-control potentiometer.

#### GENERAL ANALYSIS OF EQUIPMENT OPERATION

In the following sub-sections operational characteristics of physical elements of the flowmeter system are presented followed by discussions of environmental factors, such as solids loading and air entrainment, and their effects on the operation. Finally, specific data obtained at each site is presented.

##### Level Gauge

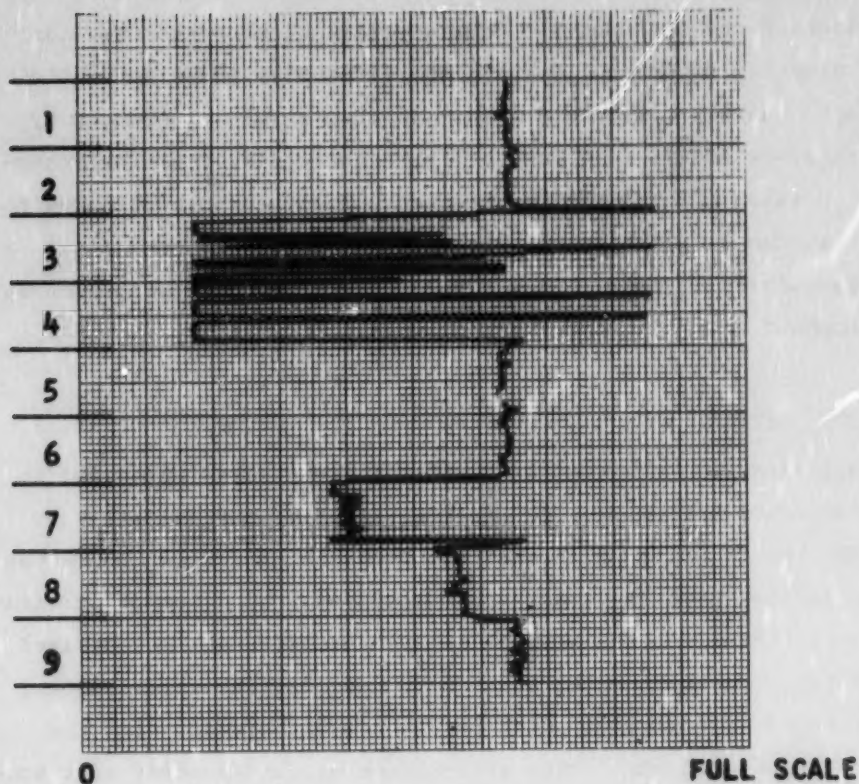
The electronic unit used to sense the liquid level was the Bin-Dicator Level Data LC-520 control with transducer LT-A and temperature compensator (South Shore installation only). The claimed electronic accuracy of  $\pm 1\%$  of full scale was met or exceeded. However, the response of the unit is somewhat faster than desirable, even when operating in the "Delayed" mode. It is possible to have sufficient surface

turbulence to reflect the ultrasonic beam at an angle outside the reception area of the transducer. Consequently noise spikes occur in the output signal. Additional damping was externally added to reduce this problem. Another possible drawback to this single transducer type of unit is the need for a dead zone of about three feet from the transducer face in which no echo can be detected. This region is blanked to allow the transducer sufficient time to damp oscillations remaining from the transmission burst. A new type of ultrasonic system presently under development will eliminate this drawback.

#### Velocity Meter Probes

The ultrasonic beam was measured in a tank of clean water and found to have a transmission cone having an included angle of approximately 8 degrees. For the Cambridge Avenue site this means good reception within a 3 inch radius about the receiving transducer. Good reception without interference from surface absorption or reflection can be obtained when the probes are submerged at least 2 inches. For the clean water, an attenuation of approximately 5 db per foot was observed, with the probes operating at 400 KHZ. This attenuation was independent of transmitter power.

Automatic Trigger Control (ATC) Performance - As discussed earlier, the electronic portion of the velocity meter was modified to include a circuit which would automatically insert a phantom trigger should the transmission path be momentarily occluded. The insertion time is based on that for the last received pulse. A test of the ATC system was made under a variety of conditions. Transmission in a channel 10 feet wide was simulated, with a full scale velocity representing 10 feet per second. The results of the test are summarized in Figure 23. Note that erroneous velocities of relatively stable appearance are generated when the missed pulses are symmetrically distributed both upstream and downstream without the ATC operating. When the symmetry is broken by randomly missing a group of pulses there is incoherence in the output without



1. NO MISSING  $R_x$  PULSES.
2. RANDOM PERIODS MISSING 1 OUT OF EVERY 10  $R_x$  PULSES, ATC 'ON' (PHANTOM PULSES INSERTED).
3. AS IN 2, EXCEPT ATC 'OFF' (NO PHANTOM PULSES INS.).
4. RANDOM PERIODS MISSING 9 OUT OF EVERY 10  $R_x$  PULSES ATC 'OFF'.
5. AS IN 4, EXCEPT ATC 'ON'.
6. MISSING 1 OUT OF EVERY 10  $R_x$  PULSES AT ALL TIMES ATC 'ON'.
7. AS IN 6, EXCEPT ATC 'OFF'.
8. MISSING 9 OUT OF EVERY 10  $R_x$  PULSES AT ALL TIMES ATC 'OFF'.
9. AS IN 8, EXCEPT ATC 'ON'.

Figure 23. ATC Performance Test

the ATC operating. This condition most nearly simulates the actual sewage channel environment. In all cases, accuracy and coherence are maintained when the ATC is operational.

Effects of Suspended Solids - An evaluation of the effects of suspended solids on the performance of the velocity measurement was undertaken both in the laboratory and in the field. Field evaluation was more qualitative than quantitative in that precise determination of the variables involved was difficult at best. For comparative purposes a quantity equal to the product of the solids loading in milligrams per liter times the ultrasonic transmission path length in meters divided by 1000 was used. For future reference this product will be called the Load-Length Product (LLP). On typical days the LLP's were determined at Cambridge Avenue, South Shore and at Jones Island. These were determined to be 0.192, 0.735 and 1.357. Of interest was the fact that the ultrasonic transmission at Cambridge Avenue Site was uninterrupted, at the South Shore Site the transmission was hopelessly occluded and at Jones Island the transmission was only intermittently blocked. Furthermore, the transmission path length at Jones Island was a full foot longer. Clearly the LLP was not by itself an adequate indicator of probable performance capability. Other variables considered were: particle size, density of particles (number per unit volume) and particle density (weight per unit volume). Although an exact theoretical or experimental treatment which includes all these variables would be essentially impossible, the following treatment is of such a nature as to indicate their general effect on the transmission intensity.

Consider a region in which there exists a number of spherical scatterers arranged in such a manner and with such separation as to preclude extensive multiple scattering. The incident wave attenuation in this region is given by the equation

$$I_i = I_{i0} \exp \{- N (\Sigma_s + \Sigma_a) x\}$$



here  $I_{io}$  is the initial incident wave intensity,  $N$  is the number of scatters per unit volume,  $x$  is the distance into the region and the  $\Sigma_s$  and  $\Sigma_a$  are defined as the scattering and absorption cross sections respectively. These cross sections are defined as the ratio of the power scattered (or absorbed) to the incident intensity.

The initial incident intensity  $I_{io}$  is given as

$$I_{io} = \frac{|A|^2}{\rho c}$$

Where  $A$  is the amplitude,  $\rho$  is the density of the medium and  $c$  is the propagation velocity in the medium.

One author has indicated that the  $\Sigma_s$  term is proportional to  $N$  for particle sizes large compared with the wave length and to  $N^2$  for those small compared with the wave length. In either event, this yields an attenuation relationship of the form.

$$I_i \sim \exp (KN^k)$$

where  $2 < k < 3$ ! Since the general characteristics of the sewage at Cambridge Avenue and South Shore were essentially believed to be the same, i.e., domestic sewage with storm runoff, this did little to explain the difficulties encountered at the South Shore Site. However, late in the demonstration grant it was discovered that the effluent from a local glue factory was discharged into the 12 $\frac{1}{2}$  foot conduit 1400 feet upstream after free-falling nearly 60 feet. Although the proximity of the glue factory was known, suspended solids levels were not sufficiently elevated to explain the transmission loss. But the certainty of large amounts of entrained air bubbles of extremely small size was then immediately recognized. Noting that the wavelength of the 400 kHz frequency in water is about 3.7 millimeters, and referring back to the equation

relating intensity to scatter site density it is easy to predict total occlusion at the site. Thus it was discovered that entrainment of very small air bubbles was the cause of blocked transmission and not suspended solids loading.

To complete the study, a laboratory study of the effects on transmission by various materials was made. The results for several representative types of materials are presented below. Note particularly the values of the LLP's.

| <u>Material</u>           | <u>Density<br/>(Milligrams per liter)</u> | <u>Occlusion<br/>Length<br/>(Meters)</u> | <u>LLP</u> |
|---------------------------|-------------------------------------------|------------------------------------------|------------|
| Rubberized<br>Horse Hair  | 19,595                                    | 0.305                                    | 5.984      |
| Open-Cell<br>Plastic Foam | 20,620                                    | 0.0658                                   | 1.357      |
| Cotton Toweling           | 265,150                                   | 0.015                                    | 3.977      |

In a separate study performed on return sludge of controlled densities, the Japanese have determined that the LLP should be less than 5.0 to ensure operation for this equipment. Note that this figure is bracketed by the horsehair and cotton toweling LLP's which are probably representative of the textural quality of part of domestic sewage. From both studies it would appear that the criteria should be that in the absence of entrained air, the LLP should not exceed 5.0

Effects of Entrained Air - Following up on the observation that entrained air had an enormously deleterious effect on the ultrasonic transmission quality, a series of experiments were performed in the laboratory. Although not intended to be highly refined or conclusive, the results are of interest. The 400 kHz probes used in the equipment were placed in clear water approximately two feet apart and the transmitter probe was

was excited in a gated continuous wave made by an oscillator times to the third harmonic, 1200 kHz. The receiver probe was monitored by an oscilloscope. In Figure 24 the receiver excitation for clear water is shown. Figures 26 and 27 show this wave packet in expanded form. Both the receiver and transmitter initially respond by resonating at their natural frequencies of 400 kHz, then finally are driven into third harmonic resonance and following the termination of the transmitter excitation, relax into their natural harmonic modes once again. Next an intense jet of water pumped from the vessel was directed through the air and directly into the water transmission medium. After a period of several seconds, when a stable entrainment condition existed, the pump was turned off. Figure 25 shows the condition of the receiver probe response at that time. Figure 28 is an expanded view of the leading edge. Note the absence of the 400 kHz excitation of the receiver transducer, although it was still present on the transmitter transducer. Clearly the 400 kHz information was impeded whereas the 1200 kHz information was not. This may indicate that difficulties with air entrainment might be reduced by operating at a higher frequency where the density of air bubbles of resonant size would be reduced. Ultrasonic transmission in the presence of entrained air at various sonic frequencies would be a fruitful area for additional investigation.

#### CAMBRIDGE AVENUE

From the very beginning of the tests, signal levels at this site have usually been quite strong. In fact, reduction in receiver and/or transmitter strength was clearly indicated. Very little difficulty with entrained solids or air was experienced, and the addition of the ATC circuit eliminated any occasional traces. A section of a typical chart recording at this location is included in Figure 29. The system at this location has continued to operate with only routine periodic maintenance for nearly 2 years. Installation diagrams for the site can be found in Section IV. Note that it is a circular conduit 5 feet

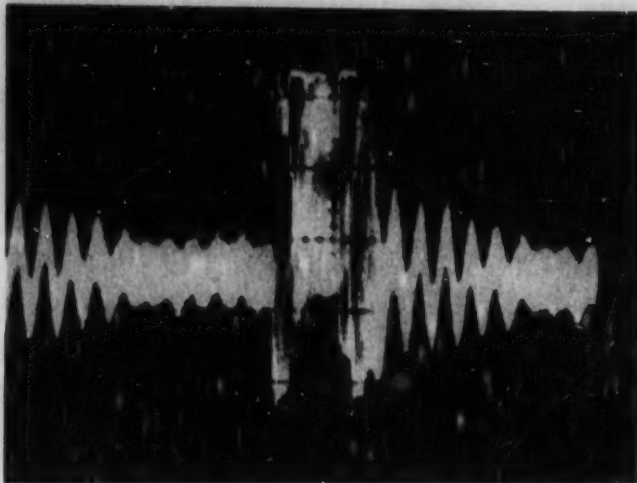


Figure 24.

Received Signal,  
Clear Water

Figure 25.

Received Signal,  
Water with Entrained  
Air Bubbles

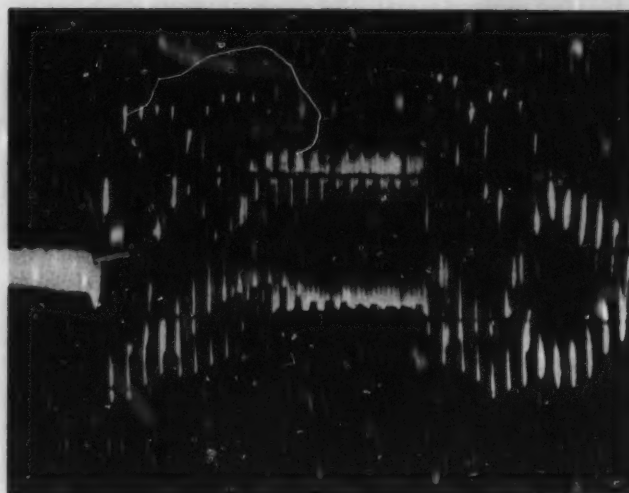
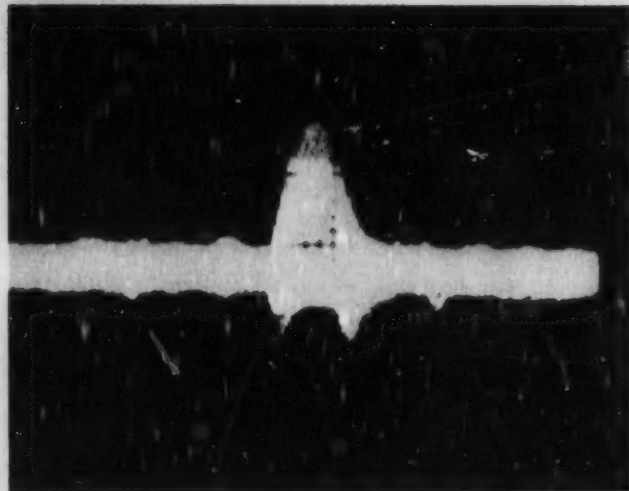


Figure 26.

Received Signal,  
Clear Water, Expanded



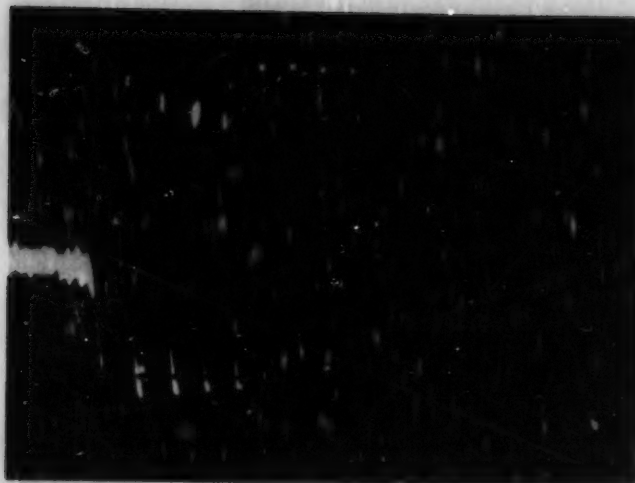


Figure 27. Received Signal, Clear Water,  
Further Expanded

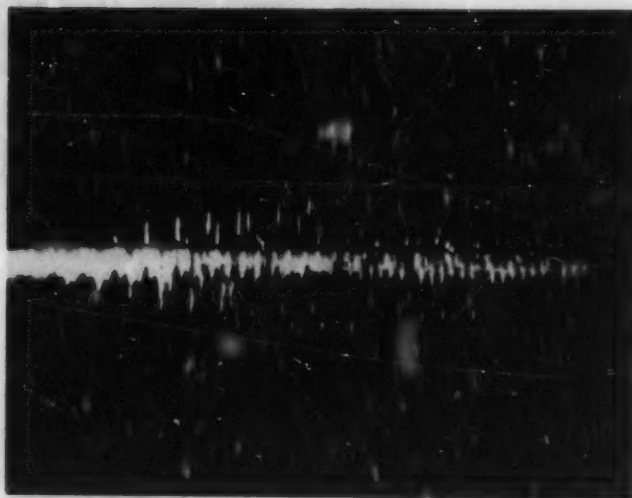


Figure 28. Received Signal, Water with Entrained  
Air Bubbles, Expanded

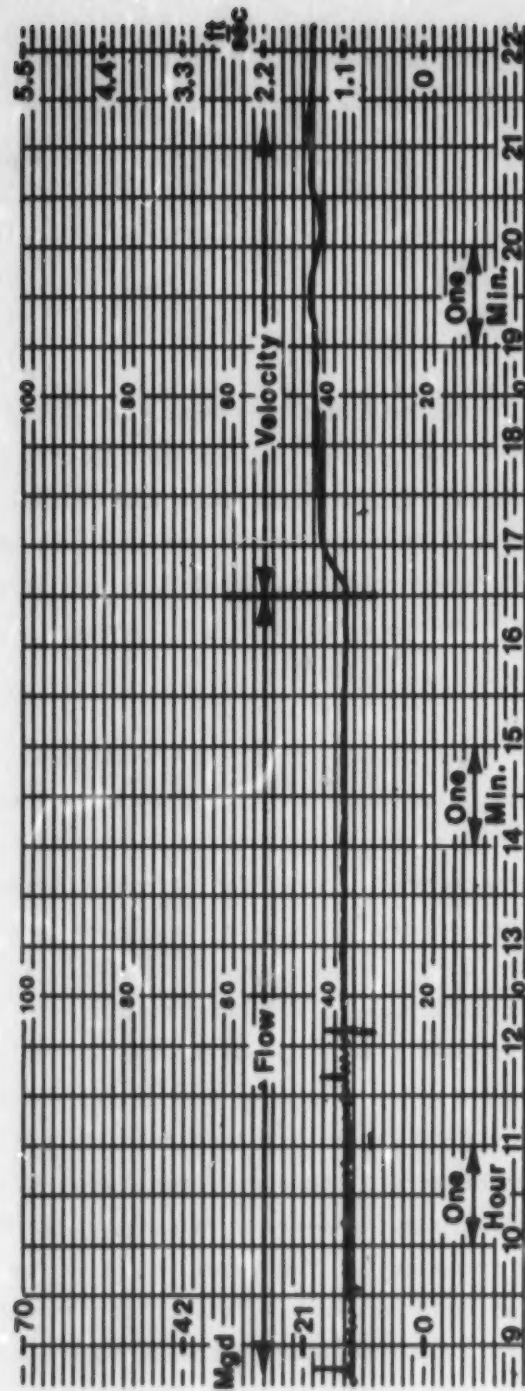


Figure 29. Typical Flow and Velocity Recordings  
Flow and Velocity Output Signals, Cambridge Avenue

in diameter with four sets of probes placed at the 1.0, 1.75, 2.5 and 3.25 foot levels. Probe face-to-face separation are summarized in the Table below.

| <u>Probe<br/>Set #</u> | <u>Level<br/>(feet)</u> | <u>Separation<br/>(feet)</u> |
|------------------------|-------------------------|------------------------------|
| 1                      | 3.25                    | 4.54                         |
| 2                      | 2.50                    | 4.88                         |
| 3                      | 1.75                    | 4.54                         |
| 4                      | 1.00                    | 3.88                         |

The velocity unit is calibrated for the separation found at both sets #1 and #3 and for a maximum or full-scale velocity of 5.5 feet per second. (The estimate is based on slope and typical flow data supplied by the Milwaukee Sewerage Commission.) Using the unit in flow rate (Q) mode by integrating the level data as discussed in an earlier section, the full-scale value is  $Q = 70$  mgd (i.e., a velocity of 5.5 fps with a level of 5.0 feet).

Of interest is a plot (see Figure 30) of the normalized area of a circular conduit, versus the depth of flow (normalized to the radius of the conduit). It was surprising to note that a least-squares fit of a linear approximation would result in a maximum error of less than 5%. And over the level range of  $0.1 < h/r < 1.9$ , constituting 90% of the range and over 99% of the occurrences, an error of less than 2.5% can be realized. For this reason, the Cambridge Avenue unit has been calibrated using an off-set linear approximation of the latter type.

As a check on the flow profiles anticipated from theoretical and observed data, the probe sets of this site were strobed manually and over a period of several minutes average velocity data was obtained at each of the lower three sets. The level was 3.10 feet during the test which occurred at 0830 on March 9, 1973. The necessary correction factors for probe sets #2 and #4, due to the different transmission

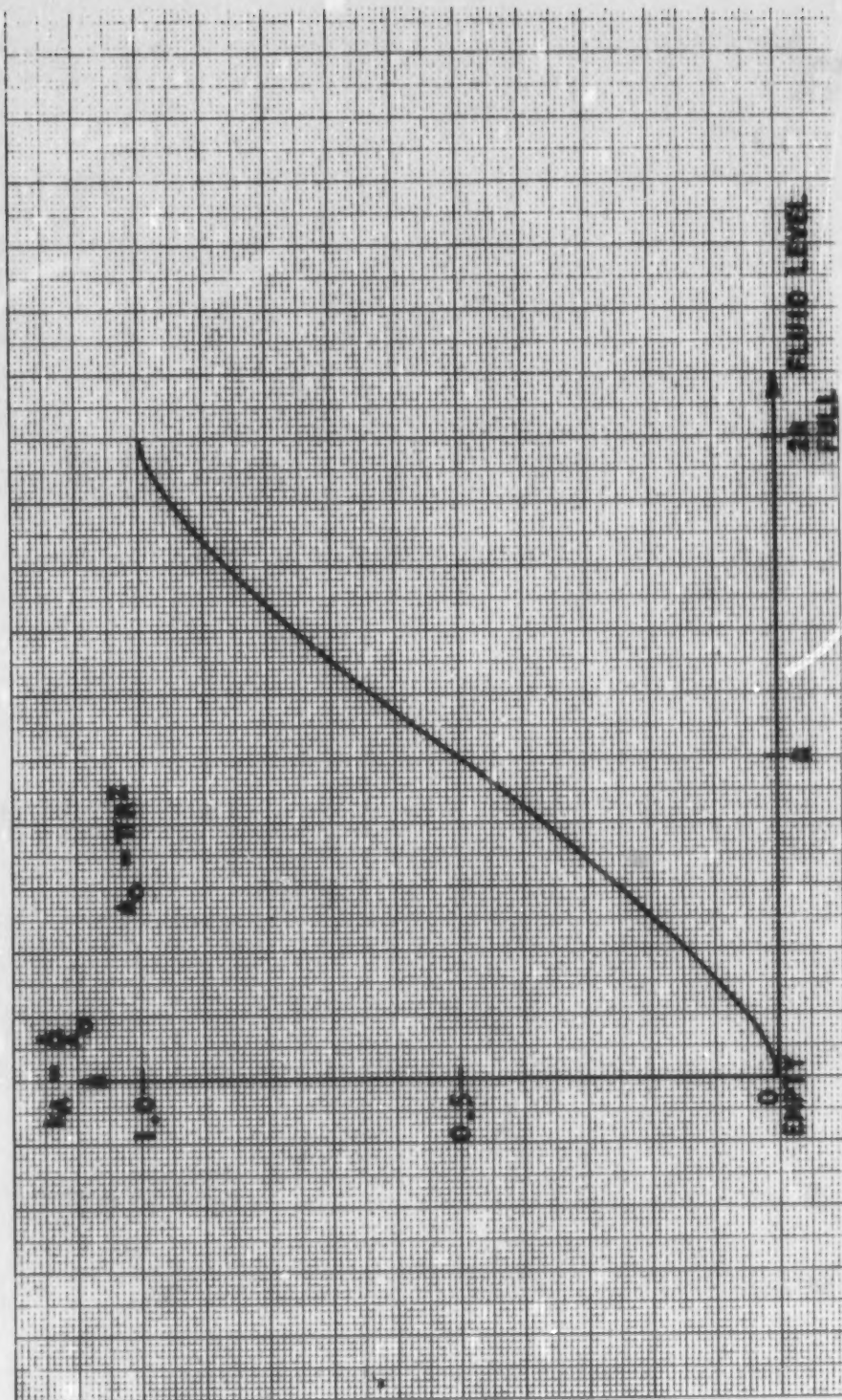


Figure 30. Area Correction Factor - Circular Pipe.



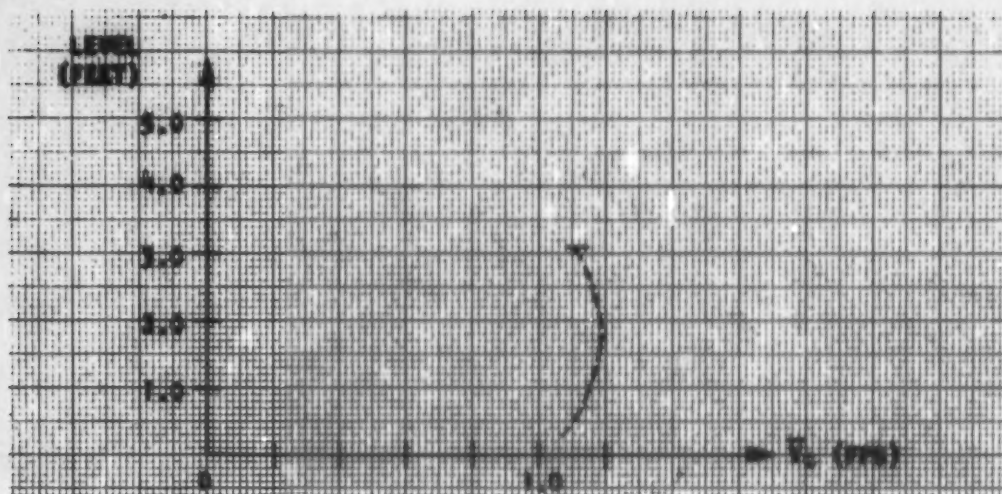


Figure 31. Measured Chordal Velocities Versus Depth, Cambridge Ave.

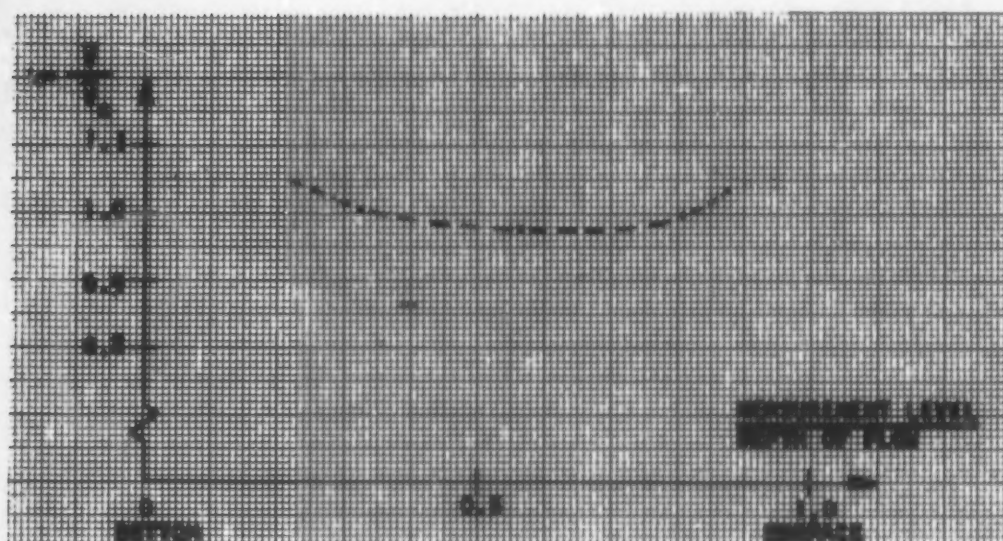


Figure 32. k-Factor Estimate, Cambridge Avenue

lengths, were applied and the results are plotted in Figure 31. By performing an area integration of  $V_c$  as shown in Figure 31, an average velocity  $\bar{v}$  is determined to be 1.15 feet per second yielding a minimum k-factor of 0.97. Note the close agreement with the value of 0.98 obtained for open circular pipes in turbulent flow. (See Appendix A for a detailed presentation of the k-factor analysis.)

Using this value of  $\bar{v}$  (1.15 feet per second) a k-factor plot is obtained and presented as Figure 32. Note again the close similarity to the k-factor plots for the circular pipes as presented in Appendix A.

Typical velocities observed at this site fall in the range of 1.0 to 2.0 feet per second, and typical levels between 3.0 and 4.0 feet. As such, typical flow extremes are approximately 8 MGD and 22 MGD. It is important to note that these flow velocities are only 20% to 40% of those predicted by use of Manning's equation, indicating that the energy slope is only a fraction of the channel slope. Retardation of the flow may be caused by the hydraulic characteristics of an inverted syphon downstream from the metering site.

#### **SOUTH SHORE TREATMENT PLANT**

As discussed in an earlier section, difficulties were experienced with the ultrasonic transmission at this site which were not fully understood, until late in the demonstration grant period, to be caused by entrained air. Installation diagrams for this site can be found in Section IV. Note that it is a circular conduit 12.5 feet in diameter with initially six sets of probes installed at the 2.0, 3.75, 5.5, 7.25, 9.0 and 10.75 foot levels. Probe face-to-face separations are summarized in the following table.

| <u>Probe<br/>Set #</u> | <u>Level<br/>(feet)</u> | <u>Separation<br/>(feet)</u> |
|------------------------|-------------------------|------------------------------|
| 1                      | 10.75                   | 8.66                         |
| 2                      | 9.0                     | 11.57                        |
| 3                      | 7.25                    | 12.78                        |
| 4                      | 5.5                     | 12.81                        |
| 5                      | 3.75                    | 11.74                        |
| 6                      | 2.0                     | 9.19                         |

The velocity unit was calibrated for the separation found at probe set #6 and for a maximum or full scale velocity of 10 feet per second. Using the unit in the flow rate (Q) mode by integrating the level data as discussed in an earlier section, the full-scale value is  $Q = 795$  MGD (i.e., a velocity of 10 fps with a level of 12.5 feet). Although the system did not perform as expected and flow level was low (about 3.0 feet) most of the time, some evaluation was possible during a period when the glue factory was not operating and during which the level could be elevated by temporarily restricting the plant input volume.

As expected, the 2-week shut-down of the Peter Cooper Plant and subsequent reduction or termination of its contribution to the South Shore Plant influent resulted in the ultrasonic velocity meter being 100% operational. This confirmed the suspicion that the occlusion of the ultrasonic signal was caused in some way by the glue factory effluent. Without doubt, this is not a typical condition which would be expected at most treatment plants. During several of these days the input flow at the South Shore Plant was purposely reduced, backfilling the 12½-foot diameter conduit to a depth of 6 to 9 feet. Flow control gates were then opened slightly permitting numerous sets of average chordal velocity readings to be obtained. This data was then plotted and correlated with the chart recordings of total plant influent. Although much of the data was obtained during hydraulic transients, graphic interpolation of the results yields flow values in close agreement with those obtained by alternate



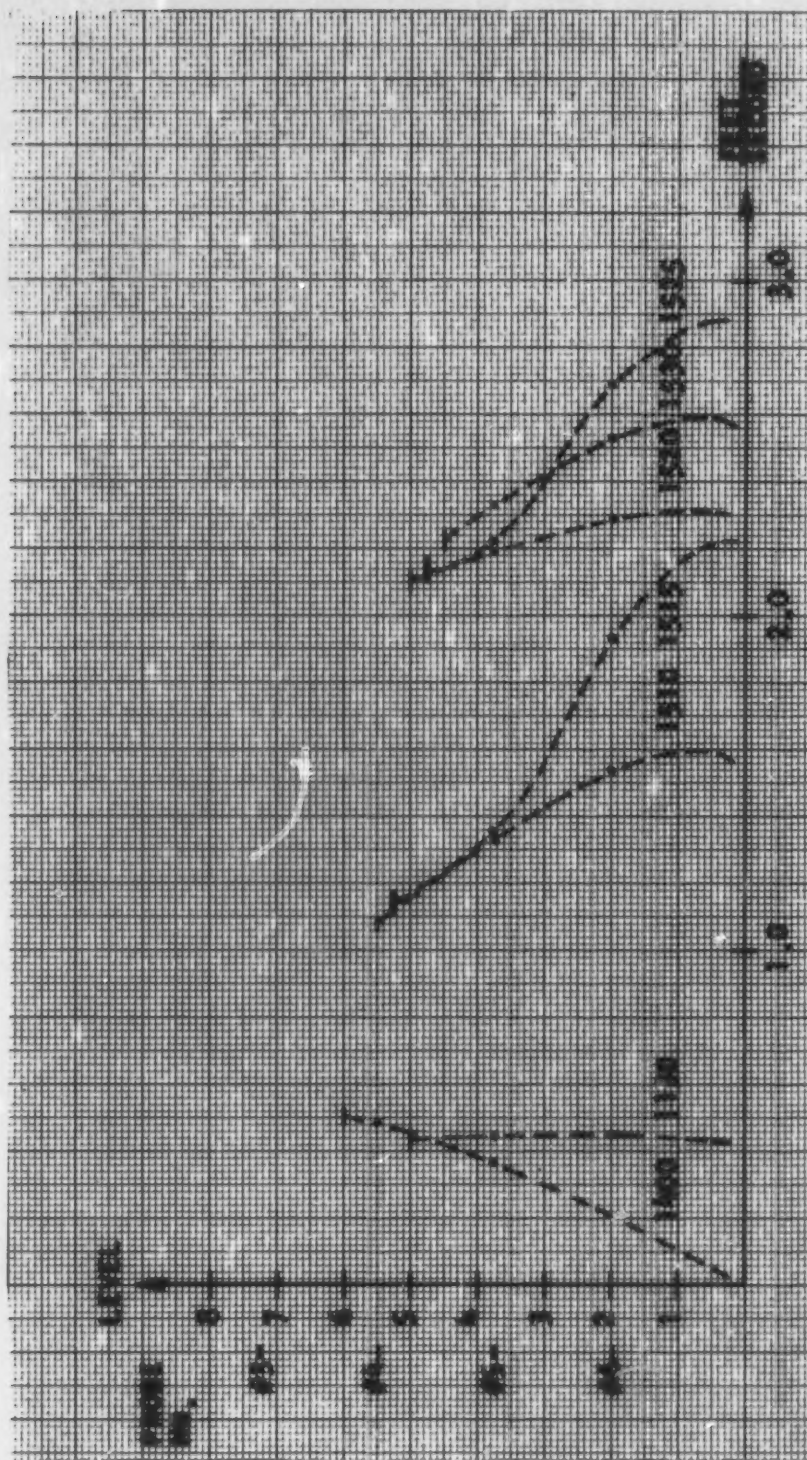


Figure 33. Measured Transient Flow Profiles, South Shore



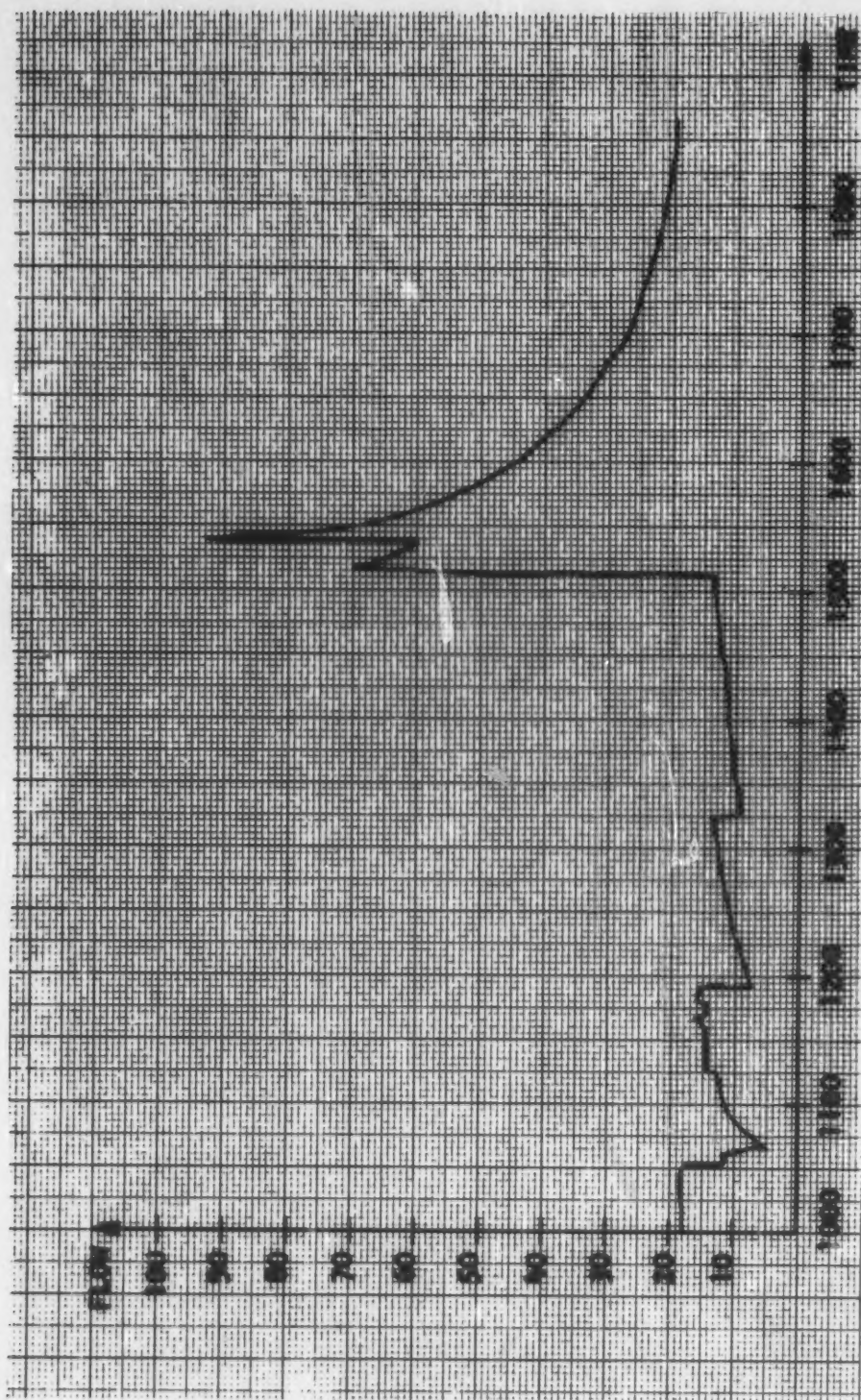


Figure 34. Mag Meter Flow Readings During Transient Tests, South Shore.

means (more specifically the mag meters downstream). Although calibration data for the mag meters was not available, the operating engineer indicated that they had been recently checked and were as accurate as could be expected considering the operating conditions. Their proximity to the ultrasonic unit precluded the need for significant time corrections due to lag. During the greater part of the morning and early afternoon of June 6, 1972, the influent flow to the South Shore Treatment Plant was significantly reduced, backing up the 12½ foot diameter conduit to a depth of 6 feet. Average chordal velocity data at the levels permitted by probe locations were recorded at depths of 5 feet (1130 hours) and 6 feet (1400 hours). The former exhibited a typically turbulent profile, whereas the latter did not, appearing more laminar. No doubt the dynamics of the filling conduit contributed to the shape. Figure 33 shows these profiles whereas Figure 34 has the corresponding plant influent flow data as recorded by mag meters further downstream (following coarse screening). Note that estimates of flow based on these profiles yield values of 13.6 MGD at 1130 (versus 14 MGD recorded) and 10.2 MGD at 1400 (versus 11 MGD recorded).

At approximately 1510 the butterfly valves downstream were partially opened, resulting in a rapid flow rate increase from about 13 MGD to 70 MGD, followed by a typically exponential decay characteristic. The gates at the conduit-plant junction permit flow into the plant from the bottom of the conduit, hence there would be a reduced flow impedance at lower levels. Although the velocity sensing elements were located approximately 60 feet upstream, the physical configuration of the gates would probably result in some dynamic effects being observed even at that distance.

The butterfly valves were again adjusted at about 1524 increasing the flow to 93 MGD briefly. Note that the effects of these two adjustments can be readily observed in both figures. Of course, the extrapolations are estimates; however, these estimates are based on observed flow

characteristics reported elsewhere (Barnes, et al). For instance, a reverse slope characteristic such as observed at 1515 is also found in circular conduits having a large slope and consequent high flow. No doubt, the shape in this case is due to the gate location, inasmuch as the profile does tend to stabilize.

Signal strength during the tests was outstanding, a situation due primarily to the fact that the Peter Cooper Glue Factory was not operating and was not discharging into the conduit.

Flows calculated from the velocity profiles measured by the ultrasonic meter agreed quite well with those measured by the plant mag meters:

| <u>Time</u> | <u>Calculated From<br/>Flow Profiles<br/>Measured<br/>Ultrasonically</u> | <u>Mag Meter<br/>Recording</u> |
|-------------|--------------------------------------------------------------------------|--------------------------------|
| 1515        | 63 MGD                                                                   | 65 MGD                         |
| 1520        | 66                                                                       | 61                             |
| 1525        | 82                                                                       | 87                             |
| 1530        | 86                                                                       | 70                             |

Again it must be reemphasized that these flow tests were run under transient conditions caused by backing up the sewer and then emptying it, by means of positioning the flow control gates at the plant inlet and thus are not entirely representative of normal flow conditions. Note under these conditions that flow profiles seem to "pivot" about a point at about 40% maximum depth, lending additional support to the procedure of locating a single set of ultrasonic probes at this depth for velocity measurements.

#### COLLEGE AVENUE

Due to the difficulties encountered at the South Shore Plant and in order to realize a full-time operating system, the top two probe sets (#1 and #2)

of the South Shore installation were removed and located in a 12 foot diameter conduit 120 feet below the intersections of College and Pennsylvania Avenues. The probe sets #1 and #2 were located at levels of 1.7 and 3.45 feet respectively (inverted from their previous positioning). Face-to-face separations of the reinstalled probes are 8.25 and 11.14 feet for the 1.7 and 3.45 foot levels respectively. The calibration of the unit was not changed and hence its use requires a correction factor equal to the ratio of the operational length to the calibration length. Installation diagrams for this site can be found in Section IV.

At this site proper operation of the velocity unit was immediately attained and continued to the end of the program with no problems of any kind. Due to the fact that this was a last minute change under a demonstration grant extension, little additional data was obtained. However, it has demonstrated conclusively that the highly agitated glue factory effluent, with its extremely high concentration of entrained air bubbles of 'resonant' size, was solely responsible for the poor performance at the South Shore Site since the sewage volume passing the College Avenue probes is the very same as that passing the South Shore probes with the solitary exception of the glue factory effluent.



## SECTION VI

### DISCUSSION OF RESULTS

#### ALLOWABLE SOLIDS LOADING & AIR ENTRAINMENT

Although existing instrumentation was applied in the demonstration for both the ultrasonic velocity and level measurements, modifications were required to suit it to the wastewater metering application. In the case of the velocity measurement, adequate pulse propagation in the presence of varying entrainments of suspended solids and air bubbles required added sophistication in the detection circuitry. Automatic gain control (AGC) was added to provide uniform detected signal amplitudes under conditions of changing received pulse energies. Even with AGC, use of leading edge pulse detection resulted in unacceptably large errors in the velocity measurement. So pulse peak detection was used instead by detecting the received pulse envelope, differentiating, and triggering on the zero crossing of the derivative.

Infrequent passage of large solids can be expected to (and did) completely block the transmission of occasional ultrasonic pulses, introducing another error into the velocity determination. This problem was minimized by automatic insertion of an external trigger pulse substituting for the missed pulse. The results of these modifications to the detection and signal processing circuitry made it possible to measure wastewater velocity accurately within the following figure of merit (Lead-Length Product, or LLP) relating the conduit diameter and solids loading:

$$(D) \times (SS) \leq 5000$$

where D is sewer diameter in meters and SS is the suspended solids con-

centration in milligrams per liter.

Solids loadings in the Cambridge Avenue and College Avenue sewers were in the range of 200 milligrams per liter, well below limiting values of 3300 and 1380 milligrams per liter respectively, so no difficulties due to solids loadings were encountered. In full pipe installations in Japan (see Appendix D) successful flow measurements are also being made on return sludge with solids loadings of 10,000 milligrams per liter in a 0.2 meter line. So for the typical conduit diameters presented in the following table no operational limitations would be expected for suspended solids loadings which did not exceed the maximum level specified:

| <u>Conduit Diameter<br/>(meters)</u> | <u>Maximum<br/>Suspended Solids<br/>Concentration milligrams per liter</u> |
|--------------------------------------|----------------------------------------------------------------------------|
| 0.2                                  | 25,000                                                                     |
| 0.3                                  | 16,700                                                                     |
| 0.6                                  | 8,300                                                                      |
| 1.0                                  | 5,000                                                                      |
| 1.5                                  | 3,300                                                                      |
| 2                                    | 2,500                                                                      |
| 3                                    | 1,700                                                                      |
| 5                                    | 1,000                                                                      |

Entrained air bubbles caused operational problems at the South Shore installation site because of dissipation of the ultrasonic pulse due to scattering by the resonant entrained air bubbles. In this installation, 20 to 50% of the sewage flow was due to a single effluent reaching the sewer from a glue factory at a point about 10 minutes upstream from the meter site. Air bubbles are generated in this effluent because it enters the main sewer via a 58.7-foot vertical drop (see Figure 11). Bubble lifetime in wastewater is longer than in tap water because of bubble adherence to solids particles. There were still enough bubbles in the sewage after a 10 minute transit time to completely occlude the

ultrasonic transmission. Accordingly, another criterion for meter installation sites is to "avoid waterfalls". In other words, select probe sites which are reasonably free of severe upstream agitation. Normal sewer flows are sufficiently quiescent so as to avoid excessive air entrainment. No entrained air difficulties were encountered at the Cambridge Avenue or College Avenue installations.

#### LEVEL GAUGE INSTALLATION CRITERION

We experienced some temporary difficulties with level gauge performance at the College Avenue Site due to standing ripples in the sewage surface which interfered with echo returns. This was alleviated by moving the level sensor a few feet to a point where the sewage surface was less disturbed, with only random surface turbulence. Inaccuracy due to occasional missed echos was satisfactorily minimized by electronic damping.

#### PROBE FOULING BY DEBRIS & GREASE

One of the major design features which was a subject of considerable conjecture before the installations were made was the possible susceptibility to fouling of the velocity probes by passing debris and grease. A major result of the program was the demonstration that this did not in fact occur, and the meters, once operational, remained in service without further attention at least for the duration of the demonstration (18 months for the Cambridge Avenue meter) and probably indefinitely. The velocity probes at the South Shore Site were inspected about a year after installation, and a quarter inch deposit on the probe face was noted. However, the systems continue to operate properly even though the sound pulses must first propagate through the deposited layer. The thickness of the deposits is apparently limited due to a balance between deposition rate and erosion rate. In other words, thicker deposits are eroded by the abrasion of passing solids, and thus build only to tolerable thicknesses. The protective housings surrounding the probes were designed to prevent the accumulation of rags, branches or other debris, and performed successfully. Materials used must be tough and noncorrodible,

stainless steel or plastic.

#### VELOCITY PROFILES & PROBE MULTIPLICITY

Another major design feature to be demonstrated was the ability to measure flow accurately with the use of only a single probe set for the velocity measurement, and a single level transducer. To accomplish this, a usable relationship between area velocity  $v_a$  and chordal velocity  $v_c$  had to be derived and applied. Using extensive flow profile data collected by Barnes<sup>4</sup> and Nikuradse<sup>5</sup>, the analysis of Appendix A demonstrates that in subcritical open channel flow,  $\bar{v}_a$  and  $\bar{v}_c$  are sufficiently close to being linearly related to enable flow to be measured within 2% over a range of depths from 35% full to full, using just a single velocity probe set mounted below the 35% level, and a single level transducer. Because of the complexity of solution for the Navier-Stokes equations for turbulent flow, an attempt was made to infer turbulent velocity profile information from laminar flow data for various channel shapes. For circular channels running full or partially filled, an apparent 6th power relationship was observed between normalized laminar chordal velocities and normalized turbulent chordal velocities. For rectangular channels, the relationship appears to be 4th power. The utility of these relationships is the ease with which average chordal velocities in turbulent flow can be obtained, as well as the subsequent computations of  $\bar{v}_a/\bar{v}_c$ , the k-factor, provides a measure of the accuracy of flow measurement based on an area velocity inferred from a single chordal velocity.

After the necessary electronic modifications were made for the wastewater application, and the South Shore test site was abandoned in favor of the College Avenue Site to avoid the air bubble problem, all equipment performed satisfactorily. Ultrasonic flow measurements checked well with current meter traversals at Jones Island (2%), and reasonably well with the transient mag meter readings at the South Shore Site. All equipment remained in operation at the close of the demonstration project.



## EQUIPMENT COSTS

At the time of the demonstration program, equipment costs were approximately \$12,200 for the ultrasonic velocity meter, \$1,200 for the ultrasonic level gauge and about \$1,600 for the mounting fixtures, cables and electrical conduits. Total system cost for each site was thus about \$15,000 (this included multiple velocity probe sets). Current costs are significantly less, being approximately \$7,500 for the ultrasonic velocity meter, \$1,000 for the ultrasonic level gauge, and \$1,000 for mounting fixtures, cables and electrical conduits, for a total system cost of about \$9,500 for each site (with a single velocity probe set).

For the large diameters metered (5' and 12'), this cost compares well with that of other flow metering devices such as venturi and magnetic meters which require full pipes for operation. It is relatively more expensive than flumes or weirs. However, the ultrasonic system continues to measure accurately when the sewer is surcharged, when weirs and flumes become inoperative. Further simplifications of the ultrasonic circuitry made possible through more extensive use of integrated circuits have the promise of further reducing the \$9,500 system cost.

## SECTION VII

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## SECTION VIII

### APPENDICES

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## APPENDIX A

### VELOCITY PROFILE ANALYSIS

Concurrently with the demonstration of the metering equipment, an investigation of velocity profiles was undertaken. This included an examination of much data for various conduit geometries and another look at the theoretical characterization of turbulent flow. The primary objective of the investigation was to obtain the relationship between the average velocity in a horizontal plane or chord ( $\bar{v}_c$ ), the level of that plane or chord ( $l$ ) and the average velocity over the entire flow cross section ( $\bar{v}_a$ ). Although it was not anticipated as a probable result of the analysis, a means of predicting the relationships between  $\bar{v}_c$ ,  $\bar{v}_a$ , and  $l$  by a computer program would have been desirable and was included as a secondary objective.

#### Experimental k-factor analysis

Having ultrasonically measured the average chordal velocity  $\bar{v}_c$  at a chord level  $l$ , it is necessary to relate this to the average area velocity  $\bar{v}_a$ . This relationship can be mathematically stated as:

$$v_a(t) = k(l, v_c) v_c(l; t)$$

where  $k$  is the proportionality factor which is a function of both the level at which  $v_c$  is determined and the value of the average chordal velocity itself. In addition, the  $k$ -factor would be expected to vary in its functional dependence on  $l$  and  $v_c$  with variations in conduit geometry.

At first glance such functional dependence and interdependences would appear to present an insurmountable barrier to successful analysis; however, it was found that there were several saving factors.

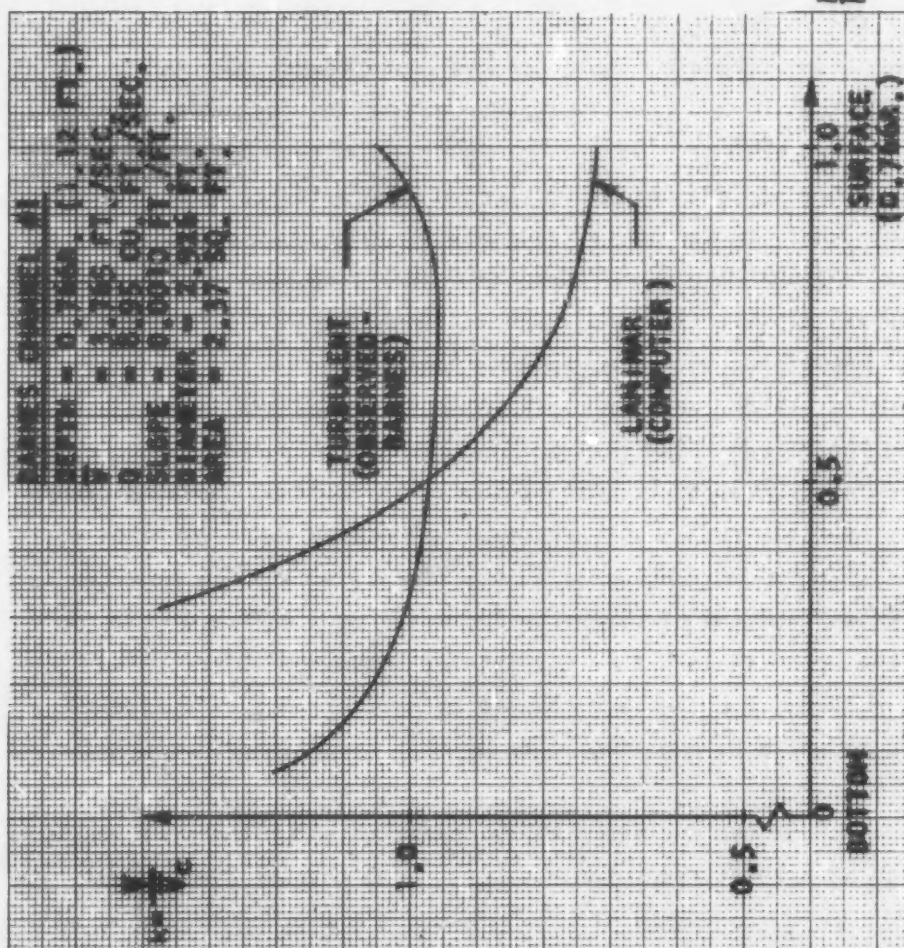


Limiting the analysis to turbulent flow, it became evident upon examining existing data from a variety of sources that the value of  $k$  is nearly independent of both level and average chordal velocity over a major portion of the depth. Furthermore, it appears to be relatively independent of conduit geometry. This is reasonable when one considers the natural asymptote of the process. In extreme turbulence it would be expected that over a major portion of the cross section the average chordal velocity, would be nearly equal to the average area velocity, i.e.,  $k = 1$ .

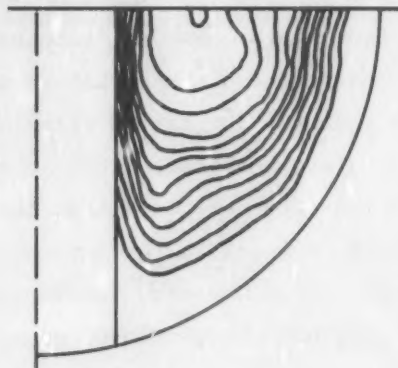
Although the Russians and Japanese have published some results of studies of the  $k$ -factor, relatively little work has been done. The difficulty is principally that of obtaining reliable data in large conduits during well-developed turbulent flow. Fortunately a great deal of reliable data was found to have been obtained during an unrelated study by Professor A. H. Barnes at Colorado State University. The apparatus used consisted of an 800 ft. long, 3 ft. diameter conduit. It was supplied by a reservoir with a 200 ft. head and had the capability of variable slope. The velocity data was obtained using propeller meters mounted on rods which could be rotated in a plane perpendicular to the conduit axis. From this data cross-sectional plots of isovels were obtained for several depths and flows. These isovel plots were then used to obtain velocity profiles in horizontal planes at various levels. Integrating these profiles and averaging over the chord length and dividing the resulting value of  $\bar{v}_c$  into the average area velocity,  $\bar{v}_a$  determined the value of  $k$  at that level. In this manner a plot of  $k$  as a function of level was obtained for that particular flow situation. In each case, a computer generated set of  $k$  values for laminar flow in a pipe filled to the same depth was obtained. Isovel diagrams for pipes roughly one third and two thirds full as well as for a full pipe are shown in Figures 35, 36 and 37 respectively, along with the  $k$ -factor plots for each.

In addition to the circular conduits, an isovel diagram of a partially full rectangular conduit, obtained and published by Nikuradse, was analyzed and the k-factors obtained. Again, a computer generated k-factor for laminar flow in a similar conduit at a similar depth was obtained. This is presented as Figure 15. In an effort to independently ascertain the value of the k-factor for a typical sewer channel, a readily accessible open rectangular channel at the Milwaukee Sewerage Commission's Jones Island Treatment Plant was studied. This channel connects the coarse-screen house and grit chamber area, is 10 feet wide and 8.5 feet deep. A Gemware magnetic type current meter of the type shown in Figure 39 was utilized in the study. Data was obtained over approximately a two hour period from 1300 to 1500 hours on September 28, 1972. During the test period the level remained at 7.06 feet with fluctuations of less than 1%. During the same period the ultrasonic velocity meter had an average indication of 4.5 ft/sec with fluctuations of  $\pm 6\%$ . Current meter readings were taken at one foot vertical intervals along the vertical center line, and verticals 2.5, 4.0 and 4.5 feet from that center line. A plot of this data is presented as Figure 40. A horizontal profile at the 2.5 foot level (the level at which the ultrasonic velocity probes are located) reflecting the values taken over the same averaging period is shown in Figure 41. Interpolation and integration yield a chordal average velocity of 4.475 ft./sec. This value calculated from the profiles measured with the current meter agrees closely with the average recorded value from the ultrasonic velocimeter of 4.5 ft./sec. Without doubt, the error is less than the inherent measurement errors encountered during the test and may not be entirely accurate itself; however, it would be expected to be of that approximate percentage.

An estimation of the average area velocity, based on the profiles in Figure 42 of 4.29 ft./sec. indicates that the chordal average velocity



ISOVELS FOR  
TURBULENT FLOW



MEASUREMENT CHORD LEVEL  
MAXIMUM FLUID DEPTH

Figure 35. Isovel Diagram, Circular Channel, 1/3 Full.

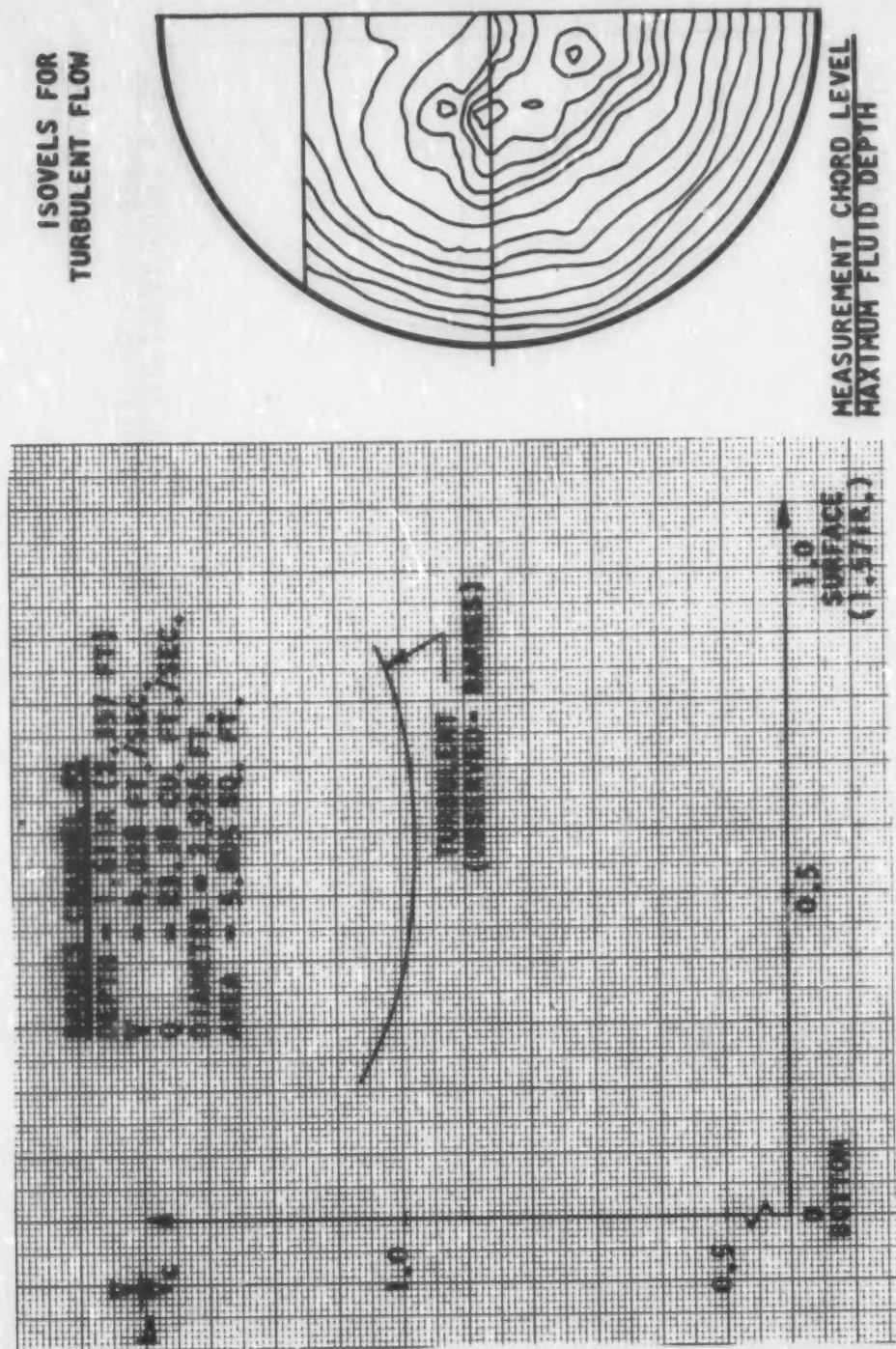


Figure 36. Isovcl Diagram, Circular Channel, 2/3 Full



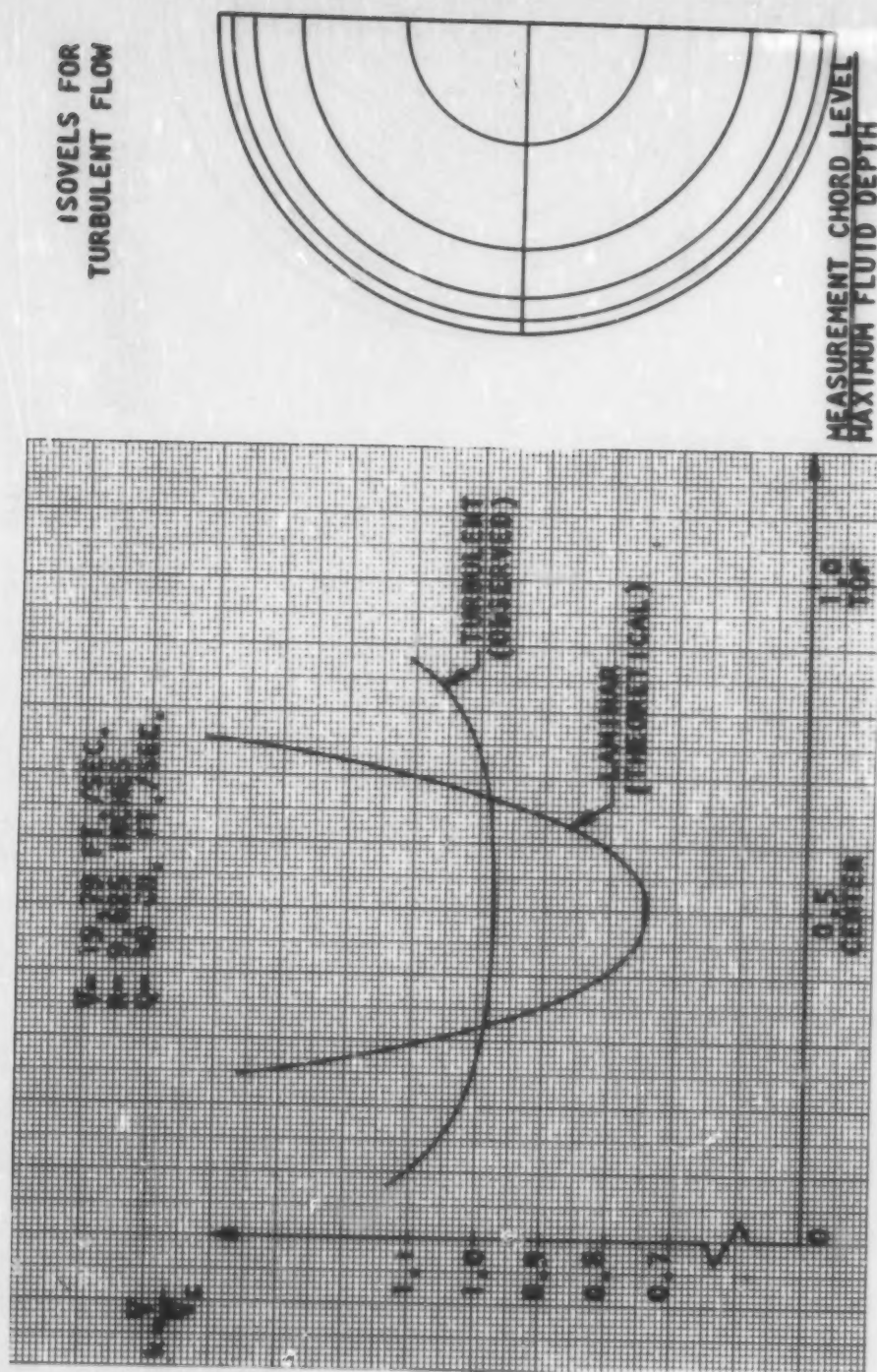


Figure 37. Isovel Diagram, Circular Channel, Full.

# ISOVELS FOR TURBULENT FLOW

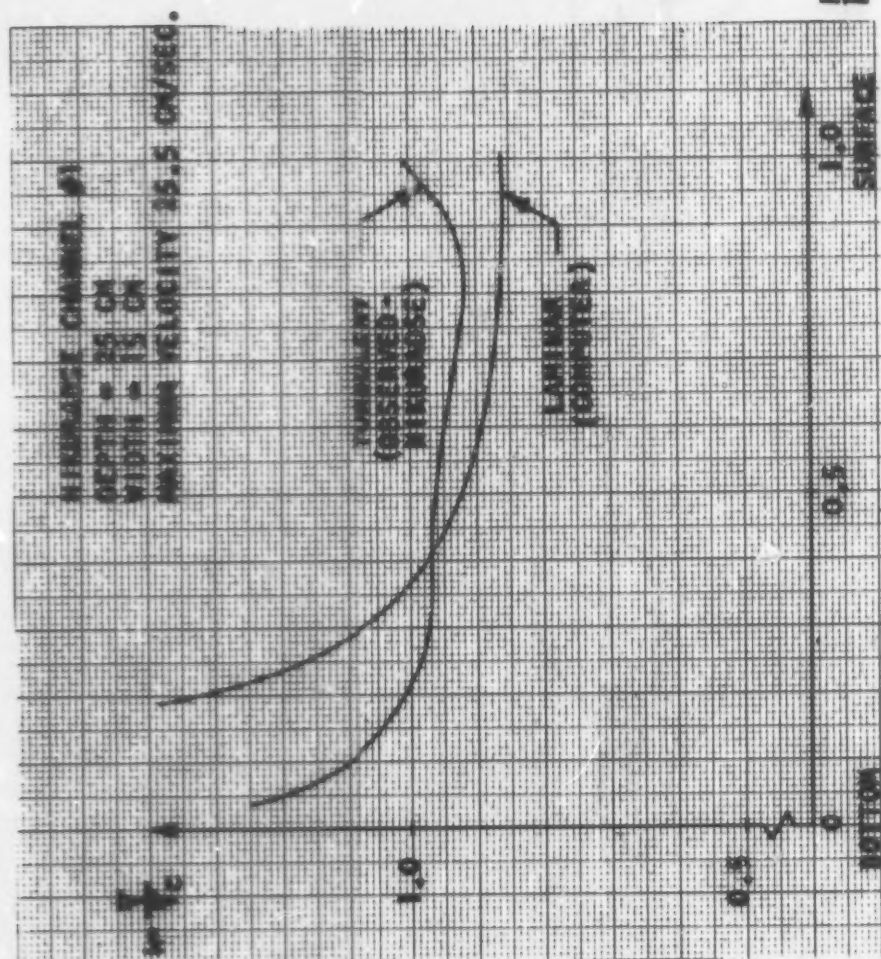


Figure 38. k-Factors, Rectangular Channel



Figure 39. Kahl-Scientific Current Meter, Exploded View

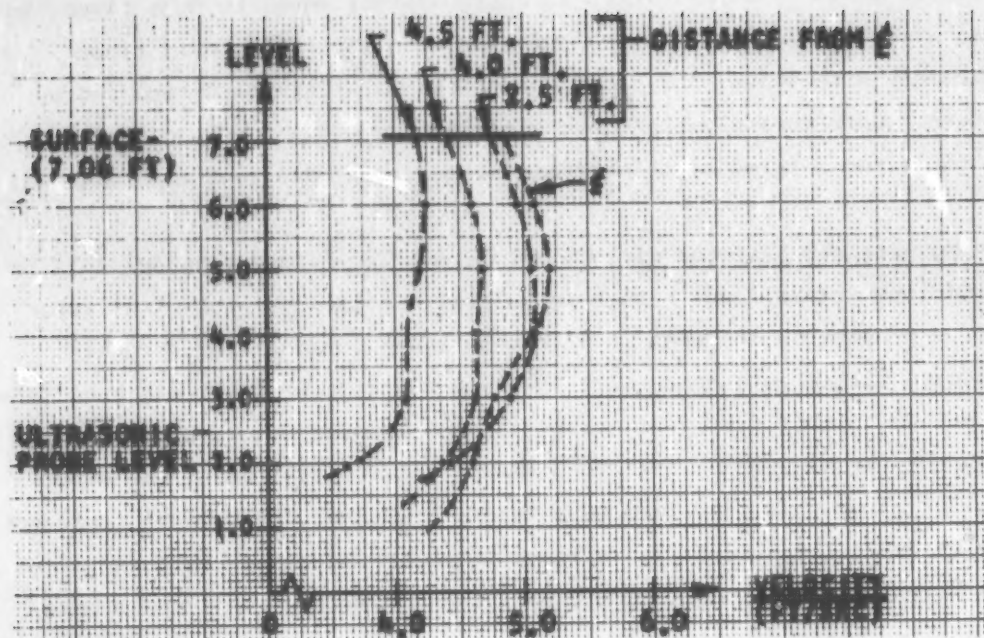


Figure 40. Vertical Velocity Profiles, Jones Island Influent Channel.

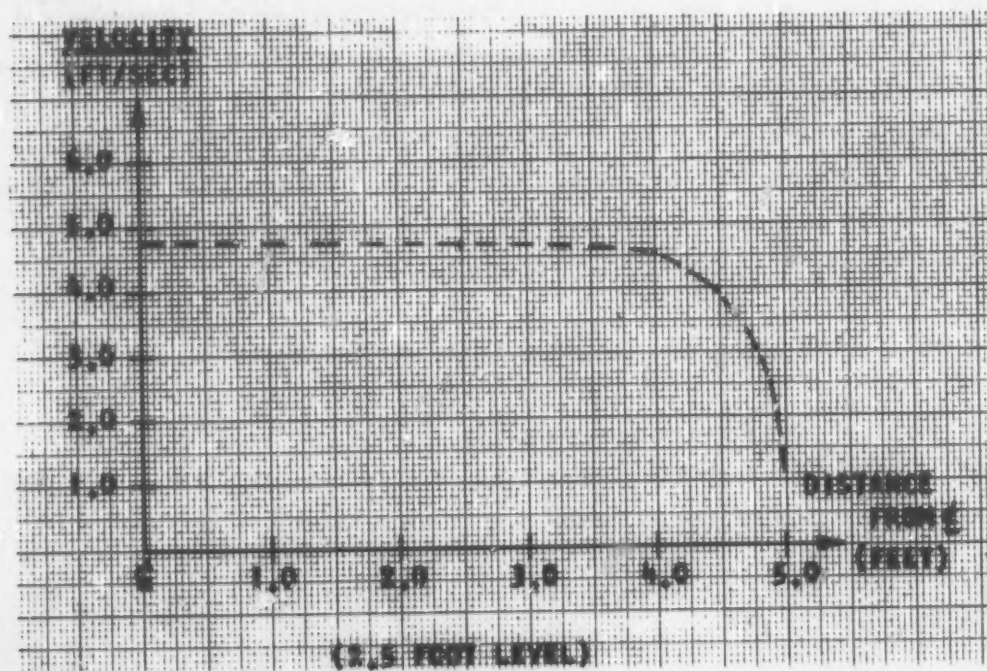


Figure 41. Horizontal Velocity Profile, Jones Island Influent Channel.



value of 4.475 feet per second is approximately equal to 0.96 times the area average velocity, i.e., a k-factor of 0.96. This is in close agreement with values for other open rectangular channels reported by others. Unfortunately the above experiment could not be repeated at any of the sites covered by this demonstration grant due to their location.

Having obtained k-factor plots versus depth for circular conduits filled to various levels, and in turbulent flow, a composite plot of k-factor versus proportion of depth (0 = bottom, 1.0 = surface) for circular conduits filled to a depth of 0.77R, 1.61R and 2.0R (full) was made (see Figure 42). This family of curves is also presented as a plot of k-factor versus liquid level (0 = empty, 2.0R = full) as Figure 20. Finally, from this last family, a family of curves (Figure 44) representing the k-factor versus liquid level as the probe chord level is varied was obtained. Although it would have been desirable to have had more data sets, there is a sufficient density of data to indicate the general trend, i.e., that velocity probes situated to measure the average velocity along the chord at a depth of 0.7R (35% of maximum) would have measured an average chordal velocity which was within 1% or 2% of the average area velocity for all flow levels between 0.7R and 2.0% (full). Some sacrifice in the constancy of the k-factor for level fluctuations would be experienced if the probes were situated at a depth less than 0.7R. (Note that as probe placement level and level of flow jointly approach 0.0R, the k-factor must asymptotically approach infinity.)

In essence, this means that by their judicious placement, a single ultrasonic velocity probe set allows sufficiently accurate (1% or 2%) measurement of the average area velocity for a wide range of levels provided that turbulent flow conditions exist. This is a result of the relative constancy of the k-factor over a wide range of depths.

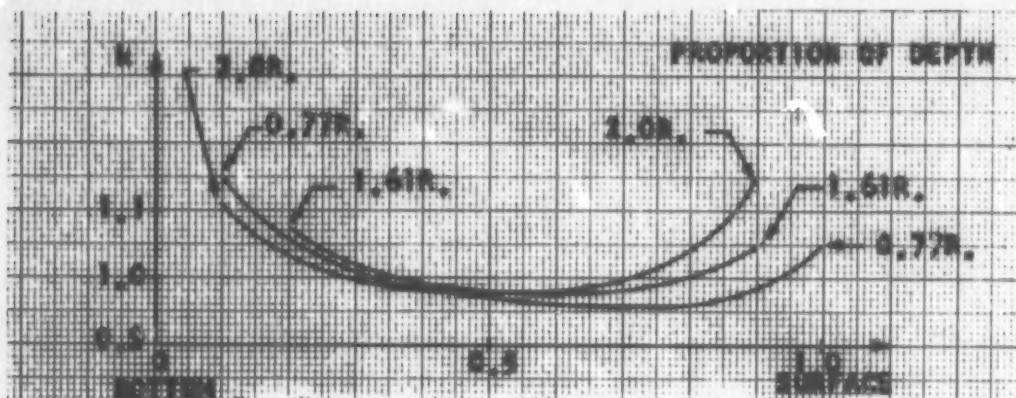


Figure 42. k-Factor Versus Proportion of Depth.

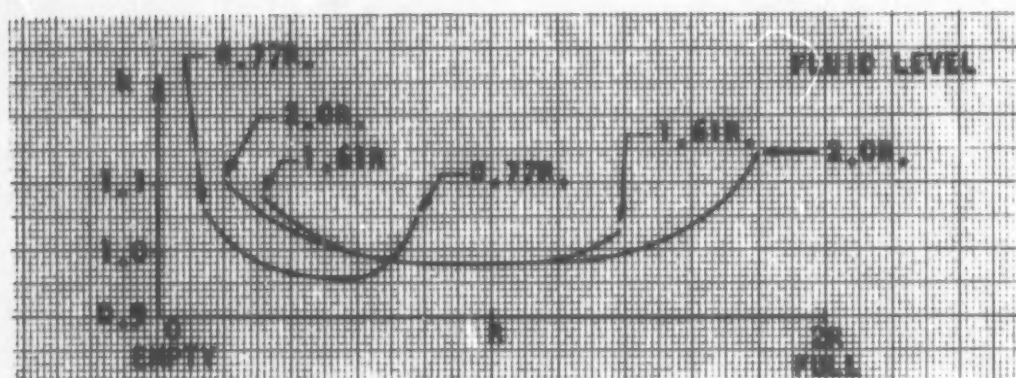


Figure 43. k-Factor Versus Liquid Level

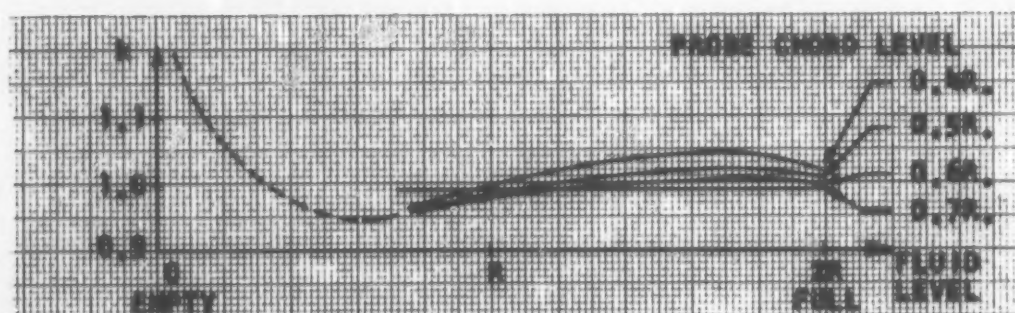


Figure 44. k-Factor Versus Liquid Level for Various Probe Chord Levels.

### Computer Aided Theoretical Analysis

A computer program was developed to present the axial velocities at cross-sectional area grid intersections for irregular shaped conduits with vertical symmetry in laminar flow. The computer program iteratively solves the Navier-Stokes equation for laminar incompressible flow given as

$$\nabla^2 v + k = 0$$

where  $v$  is the axial velocity,  $k$  is the product of the gravitational acceleration ( $g$ ) and the slope ( $s$ ) divided by the kinematic viscosity ( $\nu$ ). The boundary conditions are  $v = 0$  at the walls and, in the case of an open channel,  $\frac{\partial v}{\partial h} = 0$  at the surface (where  $h$  is the coordinate perpendicular to the surface). (The program, for an open rectangular channel, is presented in Appendix B.)

In attempting to solve this equation for either full or open (partially filled) circular channels, some thought was given to an appropriate coordinate system. The cylindrical system is the obvious choice for the full circular channel, however, it presents a number of problems when used for an open circular channel, not the least of which is the implementation of the surface boundary condition. Additional problems are encountered in maintaining a more-or-less uniform grid throughout the cross section. It appeared that the bi-polar (or bi-cylindrical) coordinate system might be a better choice. And, indeed it did facilitate the application of the surface boundary condition but made the wall-surface boundary difficult to define. Furthermore, determination of the lengths of the grid segments (needed for the iterative technique used in solving Poisson's equation) would have required either a prohibitively large number of grid points or an integration subroutine for each segment. A few trial runs proved that inadequate data accuracy resulted when a grid of reasonable size was selected and the segment lengths were approximated using standard techniques.

In view of the above difficulties, the cartesian system was again considered and found to have several features previously not appreciated; i.e., grid patterns are rectilinear (not curvilinear!), segment lengths are uniform in any given row or column (except for the last segment in a row or column) and the segment lengths are not a function of the coordinates (except at boundaries), data can be easily plotted and otherwise manipulated and boundaries for various shapes (not just rectangular or circular) can usually be easily specified mathematically. This last feature is of further significance when future solutions for channels with trapezoidal, flat-side circular and other mixed geometries are considered. Hence, a computer program was written which uses a rectilinear grid size that can also be varied within the cross section, if desired.

A trial solution for a full circular channel was obtained (using theoretically predicted values). Accuracy beyond the third place was obtained, and is deemed sufficient for the present purposes. Other trial solutions for full rectangular channels indicate the same, or better, accuracy when compared to experimental results obtained by others (notably Leutheusser).

The output consists of the velocity at each grid intersection point normalized to the velocity at the intersection of the surface and the vertical centerline. (Geometries not having symmetry about the vertical axis are not presently being considered.)

Inasmuch as the Navier-Stokes equation describing turbulent flow becomes far too complex for computer solutions on any but the largest computer systems, efforts were directed at correlating the laminar and turbulent data. The results, although incomplete, are encouraging and a correlation of sorts does appear to exist. This is discussed later.



### Full Circular Channel Analysis

As indicated above, the velocity profile for the full circular channel in the laminar region obtained by the computer agreed with that predicated on the theory. This distribution was compared to the data obtained by Nikuradse for the full circular channel in the turbulent region. The velocities along each chord were normalized to the velocity at the centerline of the chord for both the laminar and turbulent cases. This data was plotted versus the fraction of the distance along the chord from the centerline to the wall. As shown in Figure 45, the theoretical and experimental laminar data correlate exactly for all chords, and the experimental turbulent data correlates quite well for all chords considering the inherent errors involved in extracting data from the small figure in the Nikuradse paper. The fact that the normalized laminar chordal velocity distributions are identical for any normalized chord can be easily shown.

Referring to Figure 46, note that for the observed data to lie on the same line it would be necessary that the following relationship be valid.

$$\frac{v(r)}{v(1-d)} = v(L/L_c)$$

Indeed, substitution of  $L/L_c$  for  $r$  in the theoretically derived equation for a full circular channel in the laminar region:

$v = 1-r^2$  (with  $R$  and  $v_{\max}$  both unity) and the trigonometric formula for a right triangle from which  $L^2 = r^2 - (1-d)^2$  and  $L_c^2 = 1-(1-d)^2$  shows that the relationship does indeed hold, as expected.

Further study of the chordal velocity distributions for the full circular channel in the turbulent region, as given in Figure 45, seems to

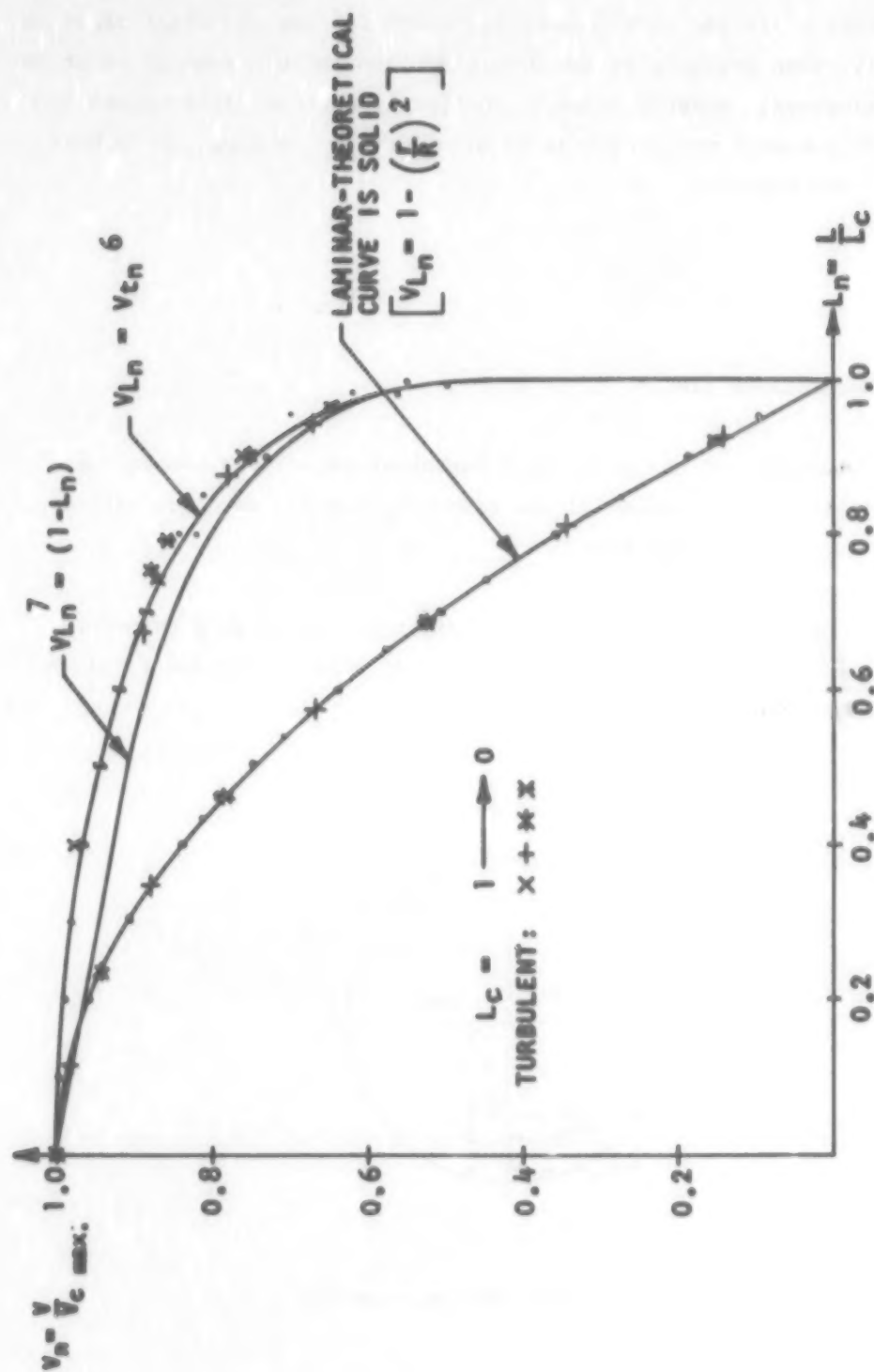


Figure 45. Experimental Versus Theoretical Velocity Data for a Full Circular Channel.

indicate that a similar relationship may exist for the turbulent case; if not exactly, then possibly it would be close enough to assume as exact in any approximation. Several attempts to approximate the distribution are shown in Figure 45, including that of Nikuradse ( $v_n^7 = r/R$ ). Note however, that the equation

$$v_{L_n} = v_{t_n}^6$$

yields a much closer fit.

Figure 47 is a plot of the normalized turbulent velocities versus the normalized laminar velocities at the same  $L/L_c$  ratio. Note how closely the 6th power relationship fits.

It would appear that this approximation might provide a good transformation relationship for converting the laminar data to turbulent values for this example.

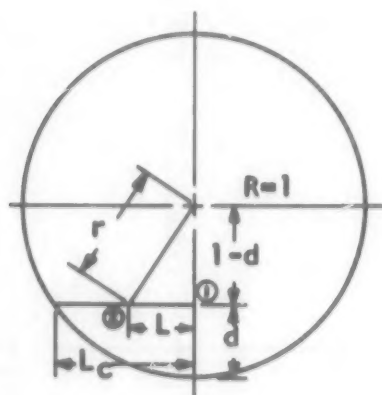


Figure 46. Circular Channel Geometry

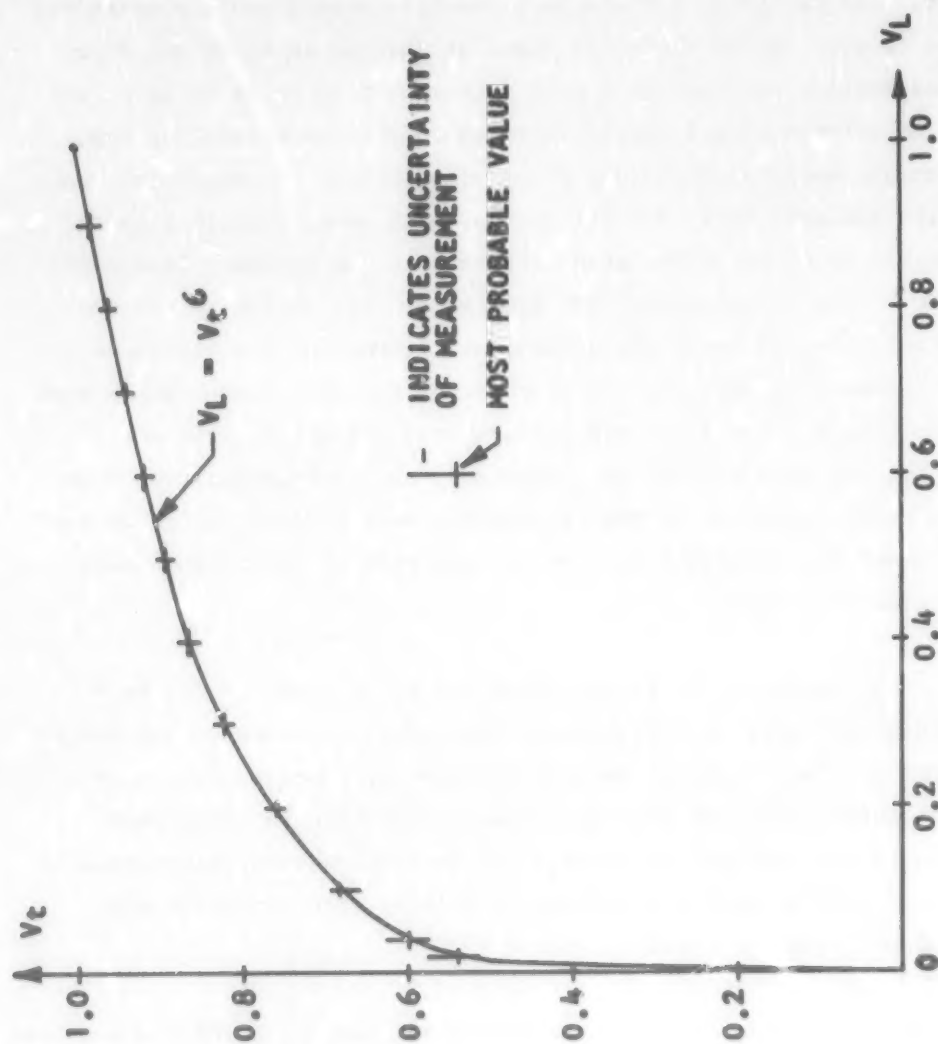


Figure 47. Normalized Turbulent Velocities Versus Normalized Laminar Velocities. Full Circular Channel.

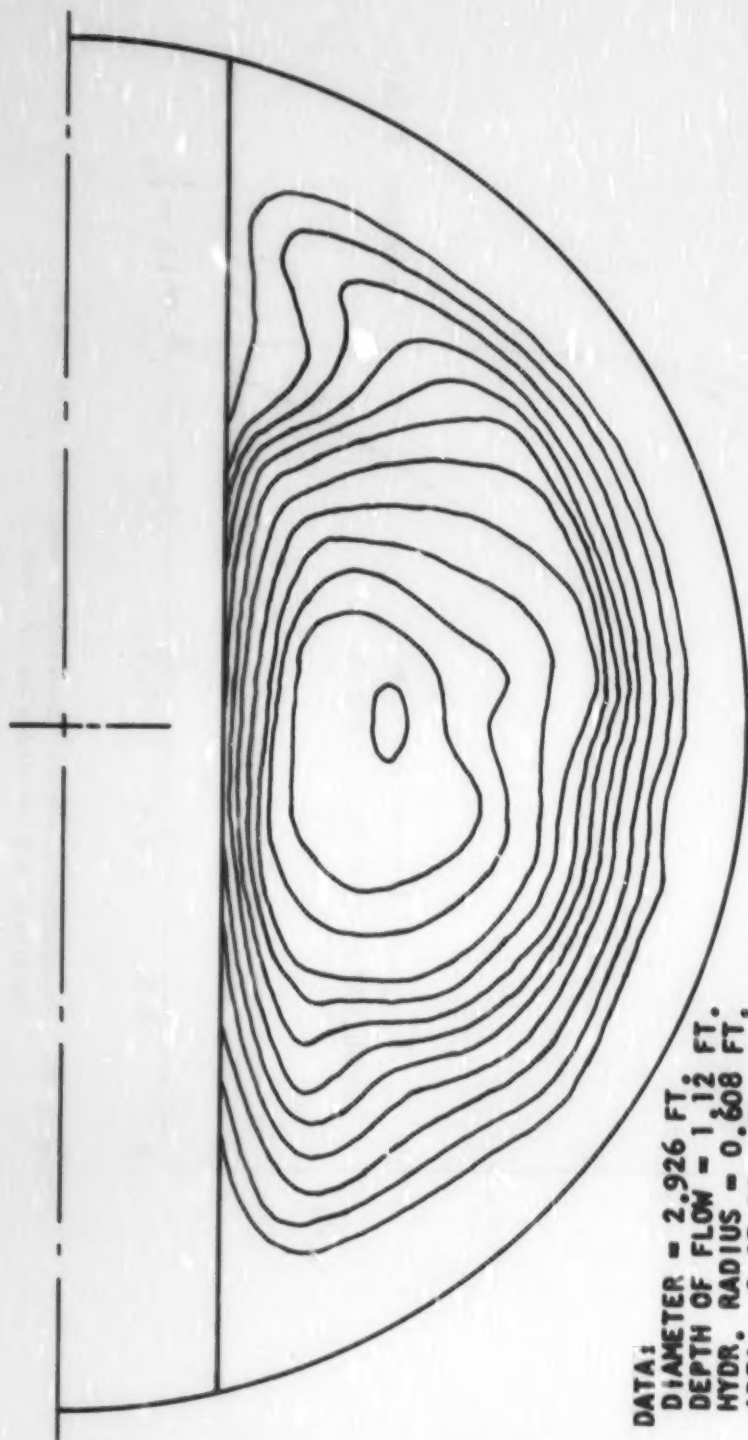


### Open Circular Channel Analysis

Using the computer program at hand, a normalized laminar velocity profile was obtained for an open circular channel of unit radius and filled to a depth of 0.766 times the radius. This was then compared, in a manner similar to that described for the full channel, with a profile presented by Barnes (Figure 48) of a similar circular channel in turbulent flow. The Barnes profile was then sectioned in such a fashion as to match the computer solution grid for the laminar case. The theoretical or experimental laminar normalized chordal velocities (Figure 49) again fall on essentially the same curve for all chords, with some deviations caused most probably by computer iteration errors near the boundary (since all deviations of any amount occur near  $L/L_c$  or for the bottom row or two of the grid). In addition, the experimental turbulent distributions indicate a strong correlation with each other for all chords (again some values for  $L/L_c > 0.8$  and for the surface grid and bottom grid are questionable inasmuch as they were obtained through interpolation from graphical representations of the raw chordal data). Also, note the good correlation of the turbulent data to the 6th root of the laminar data for any given  $L/L_c$  value.

The plot of  $v_t$  versus  $v_L$ , obtained using the plots given in Figure 49, is presented in Figure 50. It appears that the same relationship holds here as for the full circular channel. There is, however, one major difference which is not immediately evident, and this is the marked difference in the vertical profiles. One possible saving characteristic is noted and that is that the vertical profiles, when appropriately normalized, do seem to correlate well.

The apparent correlation between the normalized laminar chordal velocities and the 6th power of the normalized turbulent chordal velocities would not at first appear to have any theoretical justification. However, if one considers the viscosity to be a function of velocity, then such a



DATA:  
 DIAMETER = 2.926 FT.  
 DEPTH OF FLOW = 1.12 FT.  
 HYDR. RADIUS = 0.608 FT.  
 AREA = 2.37 SQ. FT.  
 DISCHARGE = 8.95 COMPUTED FROM ISOVELS  
               8.60 MEASURED  
 AVERAGE VEL. = 3.74 FT/SEC.  
 SLOPE = 0.0610  
 REYNOLD'S NO. = 5.44 X 10<sup>5</sup>

Figure 48. Isovells for Turbulent Flow in a Partially Filled Pipe.

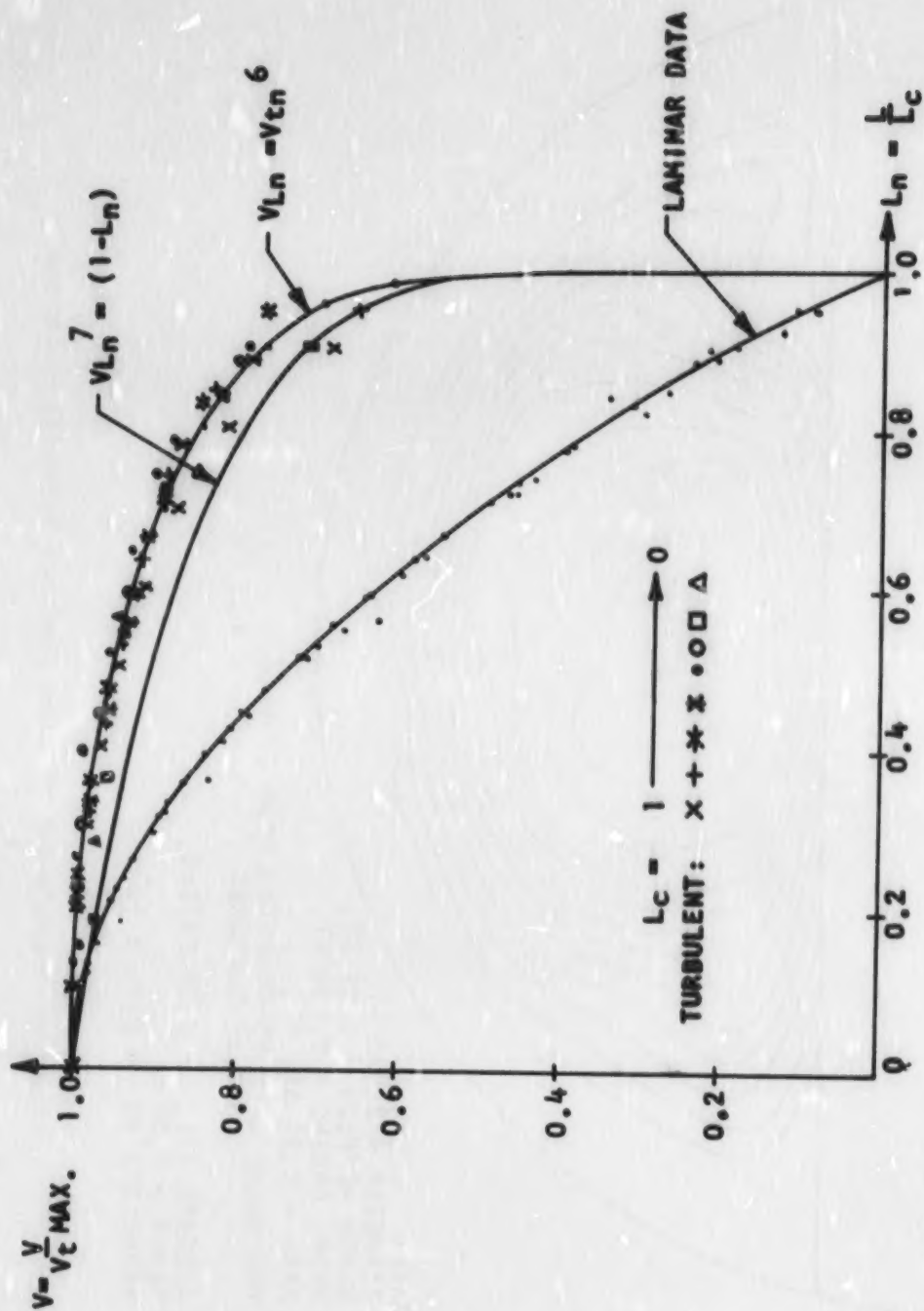


Figure 49. Experimental Versus Theoretical Velocity Data for a Partially Filled Circular Channel.

direct correlation is not only theoretically possible (see the derivation in Appendix B) but practically probable. The concept of expressing the viscosity of a turbulent fluid by a value different than that used when it is in laminar flow is discussed by Landau and Lifshitz. However, there remain two unresolved problems. First, the way in which the power in the relationship is determined is not known. For instance, under similar flow conditions the relationship between the normalized laminar velocities and the normalized turbulent velocities for the open rectangular channel appears to be fourth order, i.e.  $v_{L_n} = v_{t_n}^4$ . Second, the depression of the maximum flow velocities to levels below the surface are not explained by such a correlation. Generally, this depression is attributed to secondary flows. However, there appears to be some validity in attaining the same result by the use of proper surface boundary conditions. Such an approach is briefly alluded to by Henderson. Unfortunately, the continuation of this theoretical investigation is beyond the scope of this demonstration, although it would seem to be a worthwhile pursuit.



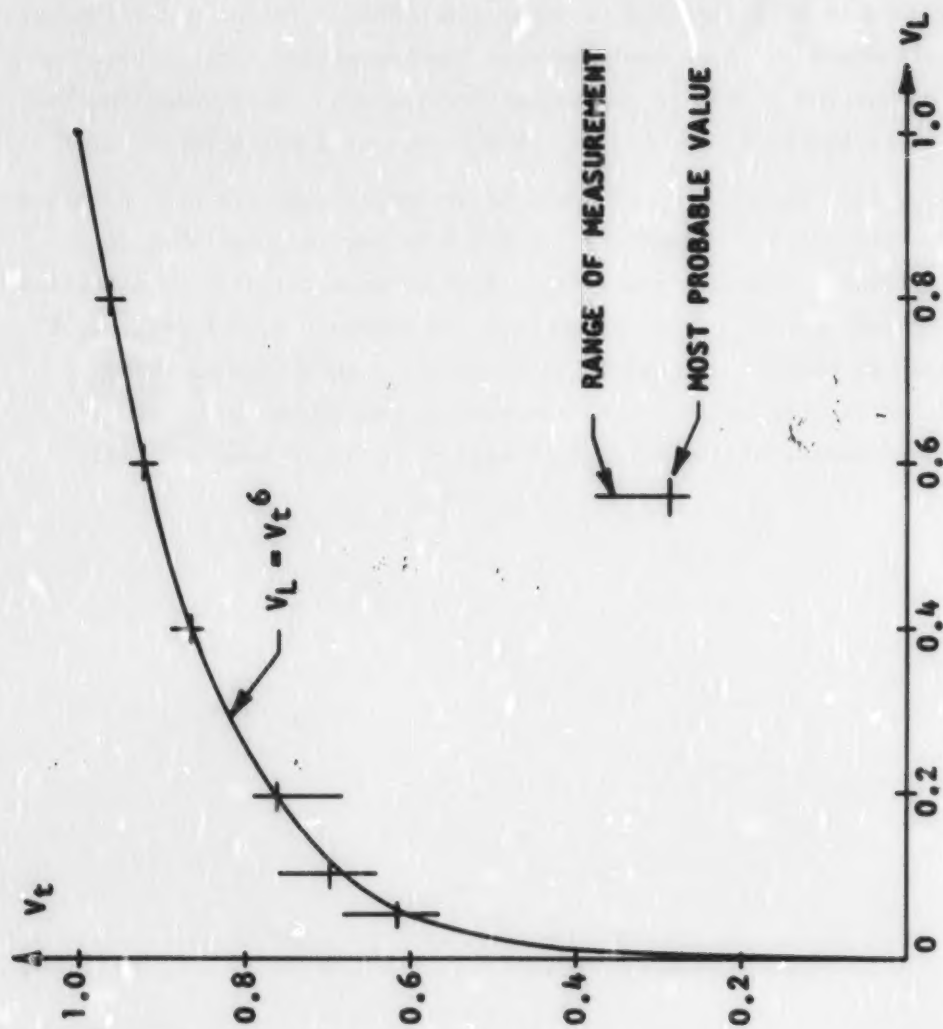


Figure 50. Normalized Turbulent Velocities Versus Normalized Laminar Velocities. Partially Filled Circular Channel

APPENDIX B

COMPUTER PROGRAM FOR SOLUTION  
OF THE  
NAVIER-STOKES EQUATIONS  
FOR  
LAMINAR FLOW IN A RECTANGULAR OPEN CHANNEL

A computer program which iteratively solves the Poisson equation

$$\nabla^2 v + k = 0$$

is presented. A cartesian coordinate system is used with a maximum grid size of 10 x 10, not including the wall boundaries (bottom and side). As shown, the program will find the laminar velocities at grid intersection points normalized to the velocity value at the center of the surface. Symmetry about the vertical centerline is assumed. The boundary condition at the surface is

$$\left. \frac{\partial v}{\partial h} \right|_{\text{surface}} = 0$$

For geometries having proper symmetry but irregular sides and/or bottom, it is necessary to modify the portions labelled: Initial Data, Row and Column Lengths and Number and Length of Each Row and Column Segment. This can be done as a data entry or by another computer program.

Output data is presented in matrix form with the average row velocity presented first for each row, followed by the centerline velocity and thence each velocity sequentially to the wall. Vertically rows are presented from the surface down to the bottom. The average velocity over the entire area is presented as a single-entry final row.

```

C      RECTANGULAR-OPEN
      DIMENSION RL(10),CL(10),NSEGR(10),NSEGC(10)
      DIMENSION RSEGL(10,10),CSEGL(10,10),C(10,10,5),V(11,11)
      DIMENSION VH(10,10),VC(10)
1     FORMAT(1X,F6.3,4X,10F6.3)
2     FORMAT(1X,F6.3)
3     FORMAT(F6.3)
C      INITIAL DATA
      READ(5,2)DLR
      READ(5,2)DLC
      NR=10
      NC=10
      A=0.0
      B=1.0
      EPS=1.0E-10
      DO 5 I=1,11
      DO 5 J=1,11
5     V(I,J)=0.0
      CK=400.0
C      ROW AND COLUMN LENGTHS
      RI=NC
      DR=RI*DLR
      RJ=NR
      DC=RJ*DLC
      DO 10 I=1,NR
10     RL(I)=DR
      DO 15 J=1,NC
15     CL(J)=DC
C      NUMBER AND LENGTH OF EACH ROW AND COLUMN SEGMENT
      DO 25 I=1,NR
      SEGN=RL(I)/DLR
      ISEGN=SEGN
      TSEGN=ISEGN
      K=1
      IF((SEGN-TSEGN).LT.0.001) K=0
      NSEGR(I)=ISEGN+K
      DO 20 J=1,ISEGN
20     RSEGL(I,J)=DLR
25     IF(K.EQ.1) RSEGL(I,ISEGN+1)=DLR*(SEGN-TSEGN)
      DO 35 J=1,NC
      SEGN=CL(J)/DLC
      ISEGN=SEGN
      TSEGN=ISEGN
      K=1
      IF((SEGN-TSEGN).LT.0.001) K=0
      NSEGC(J)=ISEGN+K
      DO 30 I=1,ISEGN
30     CSEGL(I,J)=DLC
35     IF(K.EQ.1) CSEGL(ISEGN+1,J)=DLC*(SEGN-TSEGN)

```

```

C      GRID INTERSECTION COEFFICIENTS
C(1,1,1)=A/(CSEGL(1,1)*CSEGL(1,1))
C(1,1,2)=1.0/(RSEGL(1,1)*RSEGL(1,1))
C(1,1,3)=B/(CSEGL(1,1)*CSEGL(1,1))
C(1,1,4)=C(1,1,2)
C(1,1,5)=C(1,1,1)+C(1,1,2)+C(1,1,3)+C(1,1,4)
NT=NSEGC(1)
DO 40 I=2,NT
C(I,1,1)=2.0/(CSEGL(I-1,1)*(CSEGL(I,1)+CSEGL(I-1,1)))
C(I,1,2)=1.0/(RSEGL(I,1)*RSEGL(I,1))
C(I,1,3)=2.0/(CSEGL(I,1)*(CSEGL(I,1)+CSEGL(I-1,1)))
C(I,1,4)=C(I,1,2)
40 C(I,1,5)=C(I,1,1)+C(I,1,2)+C(I,1,3)+C(I,1,4)
NT=NSEGR(1)
DO 42 J=2,NT
C(1,J,1)=A/(CSEGL(1,J)*CSEGL(1,J))
C(1,J,2)=2.0/(RSEGL(1,J-1)*(RSEGL(1,J)+RSEGL(1,J-1)))
C(1,J,3)=B/(CSEGL(1,J)*CSEGL(1,J))
C(1,J,4)=2.0/(RSEGL(1,J)*(RSEGL(1,J)+RSEGL(1,J-1)))
42 C(1,J,5)=C(1,J,1)+C(1,J,2)+C(1,J,3)+C(1,J,4)
DO 44 I=2,NR
NT=NSEGR(I)
DO 44 J=2,NT
C(I,J,1)=2.0/(CSEGL(I-1,J)*(CSEGL(I,J)+CSEGL(I-1,J)))
C(I,J,2)=2.0/(RSEGL(I,J-1)*(RSEGL(I,J)+RSEGL(I,J-1)))
C(I,J,3)=2.0/(CSEGL(I,J)*(CSEGL(I,J)+CSEGL(I-1,J)))
C(I,J,4)=2.0/(RSEGL(I,J)*(RSEGL(I,J)+RSEGL(I,J-1)))
44 C(I,J,5)=C(I,J,1)+C(I,J,2)+C(I,J,3)+C(I,J,4)
C      GRID INTERSECTION VELOCITIES
48 T=V(1,1)
V(1,1)=((C(1,1,1)+C(1,1,3))*V(2,1)
1      +(C(1,1,2)+C(1,1,4))*V(1,2)+CK)/C(1,1,5)
NT=NSEGC(1)
DO 50 I=2,NT
50 V(I,1)=(C(I,1,1)*V(I-1,1)+(C(I,1,2)+C(I,1,4))*V(I,2)
1      +C(I,1,3)*V(I+1,1)+CK)/C(I,1,5)
DO 52 J=2,NC
V(1,J)=((C(1,J,1)+C(1,J,3))*V(2,J)
1      +C(1,J,2)*V(1,J-1)+C(1,J,4)*V(1,J+1)+CK)/C(1,J,5)
NT=NSEGC(J)
DO 52 I=2,NT
52 V(I,J)=(C(I,J,1)*V(I-1,J)+C(I,J,2)*V(I,J-1)+C(I,J,3)*V(I+1,J)
1      +C(I,J,4)*V(I,J+1)+CK)/C(I,J,5)
C      ACCURACY CHECK AND NORMALIZATION
IF(ABS(V(1,1)-T).GT.EPS) GO TO 48
T=V(1,1)
DO 60 I=1,NR
NT=NSEGR(I)
DO 60 J=1,NT
60 V(I,J)=V(I,J)/T

```



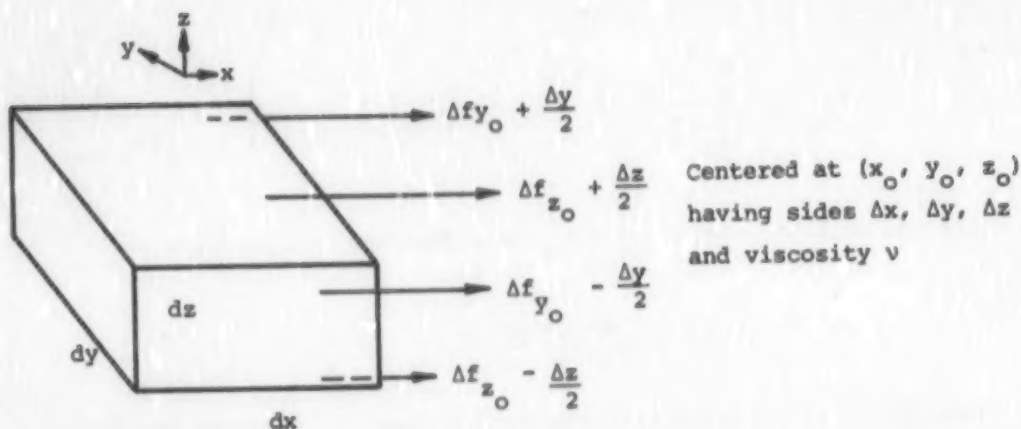
C

OUTPUT

```
62 SUMA=0
   SUMP=0
   DO 70 I=1,NR
     NT=NSEGR(I)
     RNT=NT
     SUMP=SUMP+RNT
     SUMB=0
     DO 75 K=1,NT
75  SUMB=SUMB+V(I,K)
     SUMA=SUMA+SUMB
     AVGB=SUMB/RNT
     VC(I)=AVGB
70  WRITE (3,1) AVGB, (V(I,J),J=1,NT)
     AVGA=SUMA/SUMP
     WRITE (3,2) AVGA
     DO 72 I=1,NR
       VK=AVGA/VC(I)
72  WRITE(3,2)VK
     STOP
   END
```

## APPENDIX C

### DERIVATION RELATING LAMINAR CHORDAL VELOCITY AND THE 6TH POWER OF TURBULENT CHORDAL VELOCITY



Assume that  $\eta = \eta_0 + \frac{\partial \eta}{\partial w} \Delta w$  and  $\nu = \frac{\eta}{\rho}$  with uniform  $\rho$ , then the

shear forces are

$$\Delta f_{y_0} + \frac{\Delta y}{2} = \left[ \eta_0 + \frac{\partial \eta}{\partial y} \left|_0 \frac{\Delta y}{2} \right. \right] \left[ \frac{\partial v_x}{\partial y} \left|_0 + \frac{\partial^2 v_x}{\partial y^2} \left|_0 \frac{\Delta y}{2} \right. \right] \Delta x \Delta z$$

$$\Delta f_{y_0} - \frac{\Delta y}{2} = \left[ \eta_0 - \frac{\partial \eta}{\partial y} \left|_0 \frac{\Delta y}{2} \right. \right] \left[ \frac{\partial v_x}{\partial y} \left|_0 - \frac{\partial^2 v_x}{\partial y^2} \left|_0 \frac{\Delta y}{2} \right. \right] \Delta x \Delta z$$

The difference in shear forces is  $\Delta f = \left( \Delta f_{y_0} + \frac{\Delta y}{2} \right) - \left( \Delta f_{y_0} - \frac{\Delta y}{2} \right)$ , thus

$$\Delta f = \left[ \eta_0 \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial \eta}{\partial v_x} \left( \frac{\partial v_x}{\partial y} \right)^2 \right] \Delta x \Delta y \Delta z$$

The term  $\frac{1}{\rho} \lim_{\Delta \rightarrow 0} \frac{\Delta f}{\Delta v}$  is the acceleration term due to viscosity effects ( $\Delta V = \Delta x \Delta y \Delta z$ ), and since  $\eta = \rho \nu \Rightarrow$

$$a_{v_{xy}} = \nu \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial \nu}{\partial v_x} \left[ \frac{\partial v_x}{\partial y} \right]^2$$

Including the similar term for the z direction shears, yields

$$a_{v_x} = \nu \left[ \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2} \right] + \frac{\partial \nu}{\partial v_x} \left[ \left[ \frac{\partial v_x}{\partial y} \right]^2 + \left[ \frac{\partial v_x}{\partial z} \right]^2 \right]$$

For the assumption that  $v_x \neq v_x(x)$ , this can be rewritten as

$$a_{v_x} = \nu \nabla^2 v_x + \frac{\partial \nu}{\partial v_x} (\nabla \cdot \nabla v_x)$$

Assuming that the viscosity can be expressed in terms of powers of  $v_x$ , i.e.

$$\nu = \nu_0 v_x^{n-1}$$

then

$$a_{v_x} = \frac{\nu_0}{n} \nabla^2 v_x^n$$

Assuming gravitational flow, the modified Navier-Stokes equation would be

$$\nabla^2 v_x^n + \frac{ng \sin \alpha}{\nu_0} = 0$$

where  $g$  is the gravitational constant and  $\alpha$  is the angle of inclination. Note that the laminar solution is given when  $n = 1$ .

The solution at the surface, where the equation would be given as

$$\frac{d^2 v_x^n}{dy^2} + k = 0 \quad \text{with } k = \frac{ng \sin \alpha}{v_o}, \text{ follows.}$$

Assume a width  $w$  and  $v_x = 0$  at  $y = 0$  and  $y = w$ . Then

$$v_x^n + \frac{k}{2} y^2 + C_1 y + C_2 = 0.$$

Since  $v_x = 0$  at  $y = 0$ ,  $C_2 = 0$  and evaluation at  $y = w$  yields,

$$C_1 = -\frac{k}{2} w. \quad \text{Thus}$$

$$v_x^n = \frac{k}{2} y (w-y)$$

Normalizing  $v_x$  to  $v_{x_{\max}}$  and  $y$  to  $\frac{w}{2}$  yields

$$v_x^n = y(2-y) \quad \text{with } v_{x_{\max}}^n = \frac{nw^2 g \sin \alpha}{8 v_o}$$

(Note that to be dimensionally correct  $v = v_o v_x^n$  has an implied unit coefficient whose dimension is  $(\text{sec}/\text{m})^n$ .)

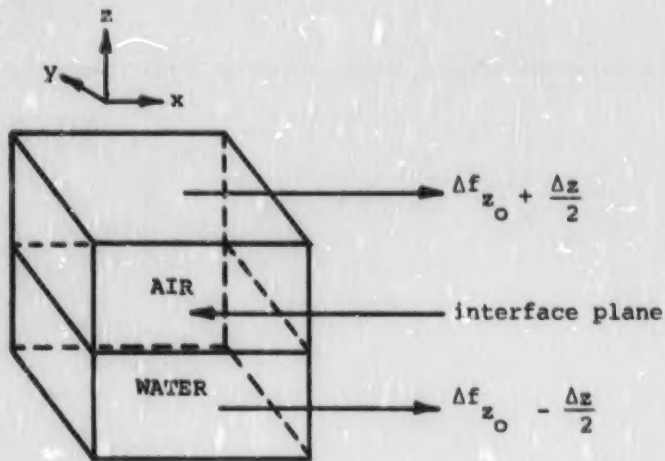
Hence

$$v_{x_{\text{turb}}} = \left[ v_{x_{\text{lam}}} \right]^{1/n}$$

This appears to work well for normalized horizontal cross sections of both circular and rectangular channels running full or open.



# Air-Water Boundary Conditions



The shear at the upper surface is

$$\Delta f_{z_0} + \frac{\Delta z}{2} = \left[ \eta_{\text{air}} + \frac{\partial \eta_{\text{air}}}{\partial z} \bigg|_0 \frac{\Delta z}{2} \right] \left[ \frac{\partial v_{\text{air}}}{\partial z} \bigg|_0 + \frac{\partial^2 v_{\text{air}}}{\partial z^2} \bigg|_0 \frac{\Delta z}{2} \right] \Delta x \Delta y$$

and at the bottom

$$\Delta f_{z_0} - \frac{\Delta z}{2} = \left[ \eta_{\text{water}} - \frac{\partial \eta_{\text{water}}}{\partial z} \bigg|_0 \frac{\Delta z}{2} \right] \left[ \frac{\partial v_{\text{water}}}{\partial z} \bigg|_0 - \frac{\partial^2 v_{\text{water}}}{\partial z^2} \bigg|_0 \frac{\Delta z}{2} \right] \Delta x \Delta y$$

Equating the two in the limit as  $\Delta z \rightarrow 0$  yields

$$\eta_{\text{air}} \frac{\partial v_{\text{air}}}{\partial z} = \eta_{\text{water}} \frac{\partial v_{\text{water}}}{\partial z} \quad (\text{at the surface})$$

Assuming that the velocities at the interface are the same yields the condition that

$$v_{x_{\text{air}}} = v_{x_{\text{water}}} \quad (\text{at the surface})$$

# APPENDIX D

## SUMMARY OF ULTRASONIC WASTEWATER METERING PERFORMANCE INSTALLATIONS IN JAPAN

During the sewage metering demonstration program conducted in the United States, ultrasonic flow measurements were also under way in Japan in eleven installations in pipes running full, seven in raw sewage and four on return sludge, made by the Tokyo Keiki Company, Ltd. The following table describes the performance of these installations:

| Metered<br>Liquid | Suspended<br>Solids<br>Concentration<br>(Milligrams/liter) | Pipe<br>Diameter<br>and Material<br>(Millimeters) | Approx.<br>Flow<br>(Cubic Meters<br>per Hour) | Remarks                                                                                   |
|-------------------|------------------------------------------------------------|---------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------------------------------------|
| Influent          |                                                            | 900<br>ductile iron                               | 5000                                          | -                                                                                         |
| Influent          | 70-100                                                     | 800<br>ductile iron                               | 3000                                          | -                                                                                         |
| Influent          | 200                                                        | 1600<br>cast iron,<br>rubber lining               | 27,000                                        | Some jitter in<br>flow record prob-<br>ably due to air<br>bubbles from pump<br>operation. |
| Influent          | 10,000                                                     | 200<br>steel, vinyl<br>lining                     | 2m/sec                                        |                                                                                           |
| Influent          | 120-130                                                    | 700<br>steel, poly-<br>urethane<br>lining         | 6000                                          | Within 1% of mag<br>meter                                                                 |
| Influent          | 4000                                                       | 500<br>cast iron,<br>moltar lining                | 1000                                          |                                                                                           |

|                  |                   |                                       |      |                                                                     |
|------------------|-------------------|---------------------------------------|------|---------------------------------------------------------------------|
| Influent         | 170               | 600<br>cast iron                      | 4000 | Within + 2.1% of<br>mag meter                                       |
| Return<br>Sludge | 10,000-<br>20,000 | 300<br>steel                          | 700  | Large transmission<br>fluctuations.<br>Within 2.1% of<br>mag meter. |
| Return<br>Sludge | 4400-9300         | 300<br>ductile iron,<br>cement lining | 500  | Within +1.2% of<br>mag meter.                                       |
| Return<br>Sludge | 6500              | 300<br>cast iron                      | 1200 | Difference with<br>mag meter - 14%.                                 |
| Return<br>Sludge | 8500-16,000       | 200<br>cast iron                      | 250  | Unstable operation                                                  |

In these installations, the ultrasonic velocimeter probes were attached to the outside of the pipe wall and sound propagation is through the pipe wall to the liquid. Note that plastic, cement or bituminous linings do not interfere with proper operation. Tokyo-Keiki has made successful experimental installations on open channels, ditches and rivers. In these, level was either controlled by constant level gates or measured with capacitance or float gages.



| TECHNICAL REPORT DATA<br>(Please read Instructions on the reverse before completing)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                    |                                         |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|-----------------------------------------|
| 1. REPORT NO.<br>EPA-600/2-76-243                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 2.                                                                 | 3. RECIPIENT'S ACCESSION NO.            |
| 4. TITLE AND SUBTITLE<br>"WASTEWATER FLOW MEASUREMENT IN SEWERS USING<br>ULTRASOUND"                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 5. REPORT DATE<br>November 1976 (Issuing Date)                     | 6. PERFORMING ORGANIZATION CODE         |
| 7. AUTHOR(S)<br>R.J. Anderson, S.S. Bell, W.H. Vander Heyden,<br>W.K. Genthe                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 8. PERFORMING ORGANIZATION REPORT NO.                              |                                         |
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| 15. SUPPLEMENTARY NOTES<br>P.O. Clifford Risley, Jr.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                    |                                         |
| 16. ABSTRACT<br>A new technique for measurement of sewage volume flow utilizing ultrasonic measurements of depth and velocity was demonstrated and evaluated. The new technique, requiring no costly construction for installation, is usable for open channel or partially full measurements. The flow technique can accomplish measurement accuracies from 2 to 5% under conditions of rapidly changing levels, surcharging, and back-up conditions. Two installations were accomplished on existing sewers in the Milwaukee Sewage System, one 12 1/2 feet and the other 5 feet in diameter. A continuous flow record was displayed for each meter and performance of the meter installations was compared with magnetic flow meters at one site and head velocity relations on the other site. Relationship between average volume flow, water level, and average velocity along selected horizontal chords of the sewer cross section were determined. The unit installed on the 5 foot diameter sewers operated for a period in excess of 18 months without failure and has required only routine maintenance. The flow technique provides accurate measurement over a range of depths from 25% to full depth in the sewer and from zero to the full flowing velocity of the fluid in the sewer. No deterioration of ultrasonic transducer probes has been detected indicating their suitability for use in the sewer environment. |                                                                    |                                         |
| 17. KEY WORDS AND DOCUMENT ANALYSIS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                    |                                         |
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